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FLAME STRENGTH OF PROPANE-OXYGEN FLAMES AT LOW PRESSURES IN TURBULENT FLOW

By Evelyn Anagnostou and A. E. Potter

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

SUMMARY

The apparent flame strength, a unique combustion measurement described previously by Potter and co-workers, was investigated for the system propane-oxygen in turbulent flow at low pressures. The dependence of flame strength on pressure and on burner diameter was determined at Reynolds numbers ranging from 2000 to 10,000, for pressure between 0.17 and 0.85 atm and burner diameters ranging from 0.398 to 0.635 cm. The results were compared with those predicted by a theory developed recently by Spalding, according to which the flame strength should vary directly with burner diameter and the pressure dependence of the flame strength should be the same as the reaction order when the Reynolds number of the flow is sufficiently high. The results of this study show that the theoretical predictions are correct, provided that the Reynolds number is over 2000.

This study shows that, under proper conditions, flame strength is a useful and meaningful measurement for characterising fuel-oxidant systems. It differs from other flame properties in that it is independent of transport properties. Its must important use may be in studying fuel-oxidant systems which are difficult to mix.

INTRODUCTION

In order to study reactive fuel-oxidant combinations not easily handled as pre-mixed systems, a unique combustion measurement, the apparent flame strength, has been described (1,2), which uses two opposed jets, one of fuel and one of oxidant. The basis for this measurement was the theoretical work of Spalding (3) and Zeldovich (4). They showed that there was a maximum flow of fuel and oxidant into the reaction zone of a diffusion flame. When this value was exceeded, the flame would go out. In the opposed-jet diffusion flame, as the mass flows of fuel and oxidant are increased, a critical flow is reached at which the flame is extinguished in an area surrounding the jet axis. The average mass flow of fuel and oxidant at the jet axis when this occurs is defined as the apparent flame strength. This is not the same quantity as Spalding's flame strength (3) but is related to it. In the body of this paper flame strength and apparent flame strength will be used interchangeably to denote the average mass flow at the flame breaking point, the quantity of references (1) and (2).

In the early theories of Zeldovich and Spalding, mass transport by diffusion alone was considered and convective flow was neglected. This was a major omission, since the diffusion flame can only be extinguished by the application of forced convection. Recently, Spalding (5) included convective flow in his theory. When he compared the theory with the experimental results of Potter, et al (1,2) he found that the experimental results did not agree with theory with respect to the dependence of the flame strength on the diameter of the burner and on the pressure.

On further analysis Spalding deduced that the actual flows in these experiments did not closely resemble the idealized flow, which was that of a jet impinging on a flat plate perpendicular to it. In order for his theory to hold, the Peclet number (i.e., $C_{p,\infty}\rho_\infty UD/\lambda_\infty$ or Reynolds number $\times$ Prandtl number) for the fuel jet should be greater than 1000 and a value of several thousand would be desirable (5). A high Peclet number infers a high Reynolds number since the Prandtl number for non-polar gases (e.g. propane) is about 0.7. The earlier work of Potter and co-workers (1,2) was done mainly with laminar flows and so these data did not fit the requirement for the theory. Therefore, the disagreement between theory and experiment is not surprising.

The present paper reports measurements of the pressure and burner diameter dependence of propane-oxygen flames at high Reynolds numbers where Spalding's theory is expected to be valid. In addition, the maximum heat release rate calculated from flame strength is compared to the rate calculated from laminar flame properties.

EXPERIMENTAL

Apparatus

A sketch of the apparatus, which is basically similar to that described in references (1) and (2), is shown in figure 1. Tubes of various inner diameters could be interchanged in the burner through the O-ring seal at the base. The burners were cooled with nitrogen gas which exhausted into the containing chamber. The burners were surrounded by a glass chimney plugged with transite at the bottom and supported rigidly by holders which were adjustable in several ways to insure alignment of the jets. The apparatus was enclosed in a large chamber with a viewing port, and the chamber was connected to a vacuum system through a scrubber containing soda lime. The pressure was maintained using two Beech-Russ pumps of 100 cfm capacity; a plenum chamber smoothed out pressure changes. The pressure was measured with a differential mercury manometer.

Procedure

The system was first evacuated and then filled with nitrogen to approximately the pressure desired. The pressure could then be maintained during a run by adjusting both the valve to the vacuum system and the nitrogen inlet valve. The fuel and oxidant were separately metered with critical flow orifices; ignition was accomplished using a spark from a molybdenum wire, embedded in the glass chimney, across to the top burner.

The measurements were made either by setting the pressure and increasing the fuel and oxidant flow or by setting the flows and slowly lowering the pressure, until a hole appeared in the flame around the jet axis. During these operations, the flame was kept midway between the two jet tubes. The hole appeared very abruptly at a flow rate or pressure reproducible to within ±5 percent. The measurements at very high Reynolds numbers were generally made by lowering the pressure at fixed flow rate, since the flames at high Reynolds numbers easily blew off with slight increases in flow rate, and were difficult to restabilize. At lower Reynolds numbers, when both techniques could be used, they gave the same results. The flame strength reported was calculated as follows: The mass flow rate at the instant of flame "breaking" was divided by the burner area to give the average mass flow rate per unit area. This was done for both the fuel and oxidant jets. The average mass flows were then multiplied by an appropriate factor to give the mass flow rate at the jet axis. This factor is 2.0 for laminar flow and 1.22 for turbulent flow. The resulting values for the fuel and oxidant jets were averaged to yield the final flame strength value. For hydrocarbon oxygen flames the oxidant and fuel flow rates do not differ by more than 10 percent.

The Reynolds numbers referred to thus far and later on in the paper are in all cases the Reynolds numbers for the propane flow. The Reynolds numbers for the oxygen flow were approximately three-eighths of those of the fuel. Even in those cases where the oxygen Reynolds number was greater than 2000, the mass flows of fuel and oxidant at the jet axis were nearly equal only when the oxygen flow was assumed to be laminar. This assumption was used for all data even though the Reynolds number for the oxygen flow was as high as 2800.

The appearance of the turbulent diffusion flames was similar to that of flames in the laminar region (1) except at the highest Reynolds numbers. As mentioned earlier, these flames were unsteady; they also tended to be smoky and to blow out rather easily.

RESULTS AND DISCUSSION

Table 1 lists the flame strength data along with burner diameter, Reynolds number, fuel and oxidant mass flows, and flame strengths corrected to a 0.462 cm diameter burner. This last quantity takes into account the dependence of flame strength on burner diameter which is discussed in the next section. Also included is a datum from reference 2, recalculated using the new burner diameter dependence.

Diameter Dependence of Apparent Flame Strength

The measured flame strengths depend on the diameter of the burner. This effect was determined at two pressures, 0.33 and 0.285 atm (9.9 inches and 8.6 inches Hg respectively) and for burner diameters from 0.398 - 0.635 cm. These data were at fuel Reynolds numbers ranging from 2030-9850. The results are shown in figure 2. Lines going through the origin have been drawn through the data. The data fit the lines to within ±5 percent, which is the over-all precision of the measurements. The indication, then, is that the flame strength is directly proportional to the burner diameter. This is precisely what Spalding's theory (5) predicts.

Effect of Reynolds Number on the Apparent Flame Strength

The theory predicts that the transport properties of the gaseous jets should have no effect on the flame strength. Hence, the flame strength is expected to be independent of Reynolds number (at least, above Re = 2000 where the theory applies.) This is found to be the case, as shown in table 2, where the flame strength at constant pressure, and constant (corrected) jet diameter is given for Reynolds numbers ranging from 2.93 to 9.07×10^3.

Pressure Dependence of Apparent Flame Strength

Figure 3 shows the effect of pressure on the apparent flame strength of the propane-oxygen system. Since there is an effect of burner diameter, the data must be referred to a single diameter. Most of the data are for a 0.462 cm burner covering a pressure range of 0.24 to 0.48 atm. The data for the other burner diameters have been converted to this diameter, using the diameter dependence established in figure 2, to extend the pressure range of the correlation at both the high and low end. The least-squares slope of the line drawn through the data is 2.0.

The slope should be close to the order of the reaction since according to Spalding, the apparent flame strength is directly proportional to the maximum reaction rate in the flame. The slope of 2.0 agrees well with the reaction order of 2.1 found from quenching distance experiments (6).

Calculation of Maximum Heat Release Rate

It is possible to calculate a maximum heat release rate using the value of the flame strength extrapolated to one atmosphere.

From Spalding's theory (5), the maximum volumetric reaction rate is

$$\dot{m}'''_{fu,\,max} = \frac{\rho}{\rho_\infty}\,\frac{\rho_\infty U_{ext}}{D}\,\frac{m_{fu,\infty}\Omega^2_{st}}{2\bar{\Psi}_{st} f_{st}}$$

By multiplying $\dot{m}'''_{fu,max}$ by the heat of combustion of propane, one obtains the volumetric heat release

$$\dot{q}'''_{max} = 5.4\times 10^4 \text{ cal/cm}^3\text{sec}$$

This value should be multiplied by a correction factor between 1.5 and 3 which accounts for viscous and density effects on the jet velocity (5).

Bittker and Brokaw (7) have reported a method of determining chemical space heating rates using properties of the laminar flame. Their equation is

$$\dot{q}'''_{max} = \frac{F}{K\left[\Gamma(n + 1)\right]}\left(\frac{E}{RT_f}\right)\left(\frac{T_f - T_o}{T_f}\right)\left(\frac{n}{e}\right)^n \times \left(\frac{C_p}{2\lambda}\right)\left(\frac{p}{RT_o}\right)U_f^2 \, \Delta H_v$$

The value of $\dot{q}'''_{max}$ obtained from this equation is 170×10^4 cal/cm^{3}sec.

The discrepancy between these two values is somewhat greater than one order of magnitude. The reason for this difference is not now apparent, but may be revealed in further theoretical studies.

CONCLUDING REMARKS

It has been shown that the opposed-jet diffusion flame yields apparent flame strength data which corroborate Spalding's theory, (5) if the precaution is taken to keep the flows high enough to conform to the idealized flow, which is that of a jet impinging on a flat plate perpendicular to it. The method can now be extended to other systems of interest (for example, those using fluorine or chlorine as an oxidizer) with some assurance that it is a true measure of maximum reaction rate in the flame.

SYMBOLS

C_p heat capacity at constant pressure

$C_{p,\infty}$ heat capacity of the fuel at constant pressure

D	diameter of the burner
E	activation energy
e	base of natural logarithms
F	conversion factor
f_{st}	mass fraction
ΔH_v	volumetric heat of combustion
K	correction factor
$m_{fu,\infty}$	mass fraction of fuel in the fuel-bearing stream
$\dot{m}'''_{fu,max}$	maximum volumetric reaction rate
n	reaction order
p	pressure
R	gas constant
T_f	flame temperature
T_o	initial temperature
U	jet velocity far upstream of the impingement region
U_f	burning velocity
Γ	the gamma function
λ	thermal conductivity
λ_∞	thermal conductivity of the fuel
ρ	density
ρ_∞	density of the fuel
$\rho_\infty U_{ext}$	flame strength
$\bar{\Psi}_{st}$	average flame reaction rate at stoichiometric
Ω_{st}	a function of f_{st}, indicative of the burning rate in the flame at stoichiometric

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TABLE 2. - FLAME STRENGTH DATA FOR TURBULENT

PROPANE-OXYGEN FLAMES

Pressure atm	Burner diameter cm	Flame strength gm/cm^{3}sec	Flame strength (corr. to 0.462 cm burner)	Fuel Re number	Mass flow at estinguishment (gm/sec)	
					Fuel	Oxidant
				×10^3		
0.291	0.635	1.12†	0.815	6.81	.272	.187
.331		1.46†	1.05	8.85	.353	.247
~~.169~~		~~.400~~	~~.292~~	~~2.49~~	~~.0995~~	.0655
.313		1.41	1.03	8.74	.348	.233
.331		1.51†	1.10	9.85	.393	.237
.261		.724	.526	4.61	.184	.117
.167		.375	.273	2.17	.0865	.0657
.285	.619	1.07†	.800	6.91	.269	.161
.331		1.49†	1.11	9.07	.367	.225
.338		1.49†	1.11	9.44	.353	.233
.334	.546	1.19†	1.00	6.28	.220	.145
.285		.915†	.774	5.29	.185	.101
.282		.901†	.762	5.29	.185	.0982
.288	.462	.750†		3.12	.091	.071
.285		.738†		3.20	.093	.068
.292		.764†		3.58	.1042	.0647
.482		2.58		11.2	.325	.236
.454		2.28		10.0	.291	.207
.420		1.80		8.0	.232	.160
.331		1.005†		4.51	.131	.089
.331		1.05†		5.09	.148	.087
.246		.517		2.10	.0610	.0497
.242		.513		2.17	.0630	.0484
.331	.398	.876†	1.02	2.93	.0733	.0641
.288		.650†	.755	2.03	.0508	.0498
.382	.321	.920	1.32	2.76	.0555	.0406
.346		.743	1.07	2.10	.0423	.0342
.478		1.37	1.95	4.60	.0928	.0539
.846	.168	2.18	6.00	3.02	.0318	.0291
.975	.168	3.51	9.66	Ref. (2)		

†Data for figure 2.

TABLE 2. - EFFECT OF REYNOLDS NUMBER

ON FLAME STRENGTH

Pressure atm	Burner Diameter cm	Flame strength (corrected to 0.462 cm burner)	Reynolds number
			$\times 10^3$
0.331	0.635	1.05	8.85
↓	.635	1.10	9.85
↓	.619	1.11	9.07
↓	.462	1.00	4.51
↓	.462	1.05	5.09
↓	.398	1.02	2.93

E-1641

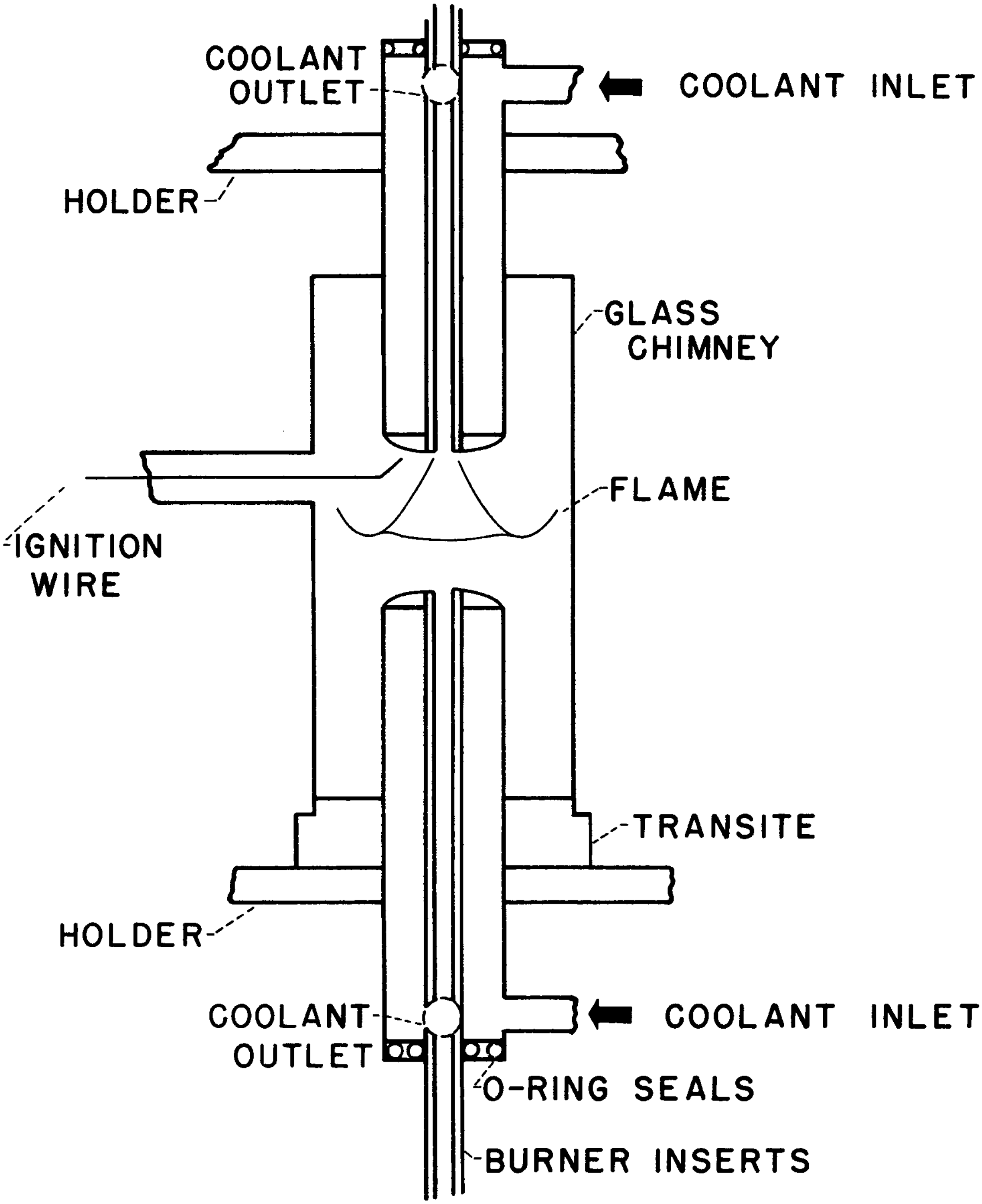

Fig. 1. Burner assembly.

E-1641

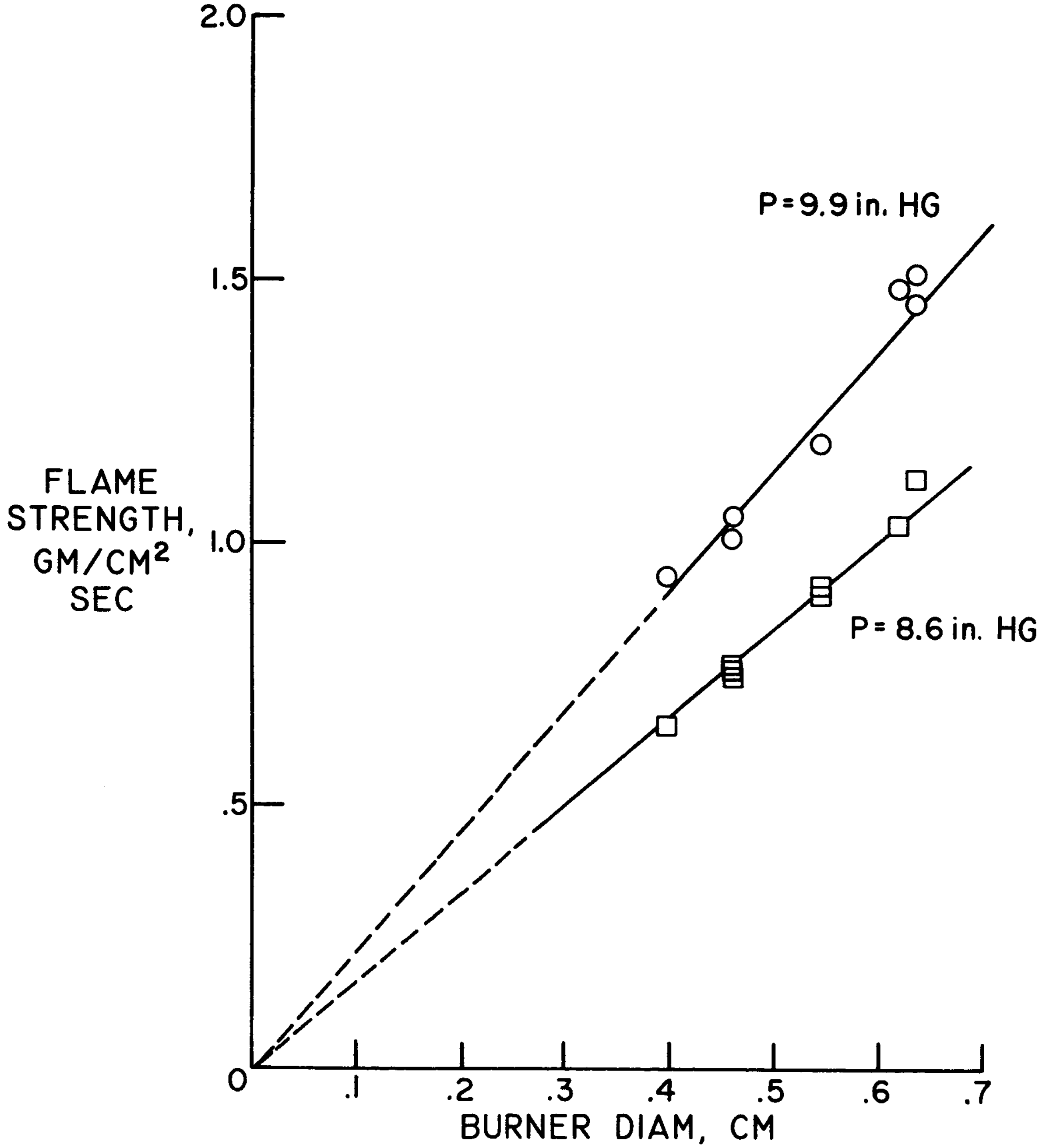

Fig. 2. Dependence of flame strength on burner diameter at two pressures for the propane-oxygen system.

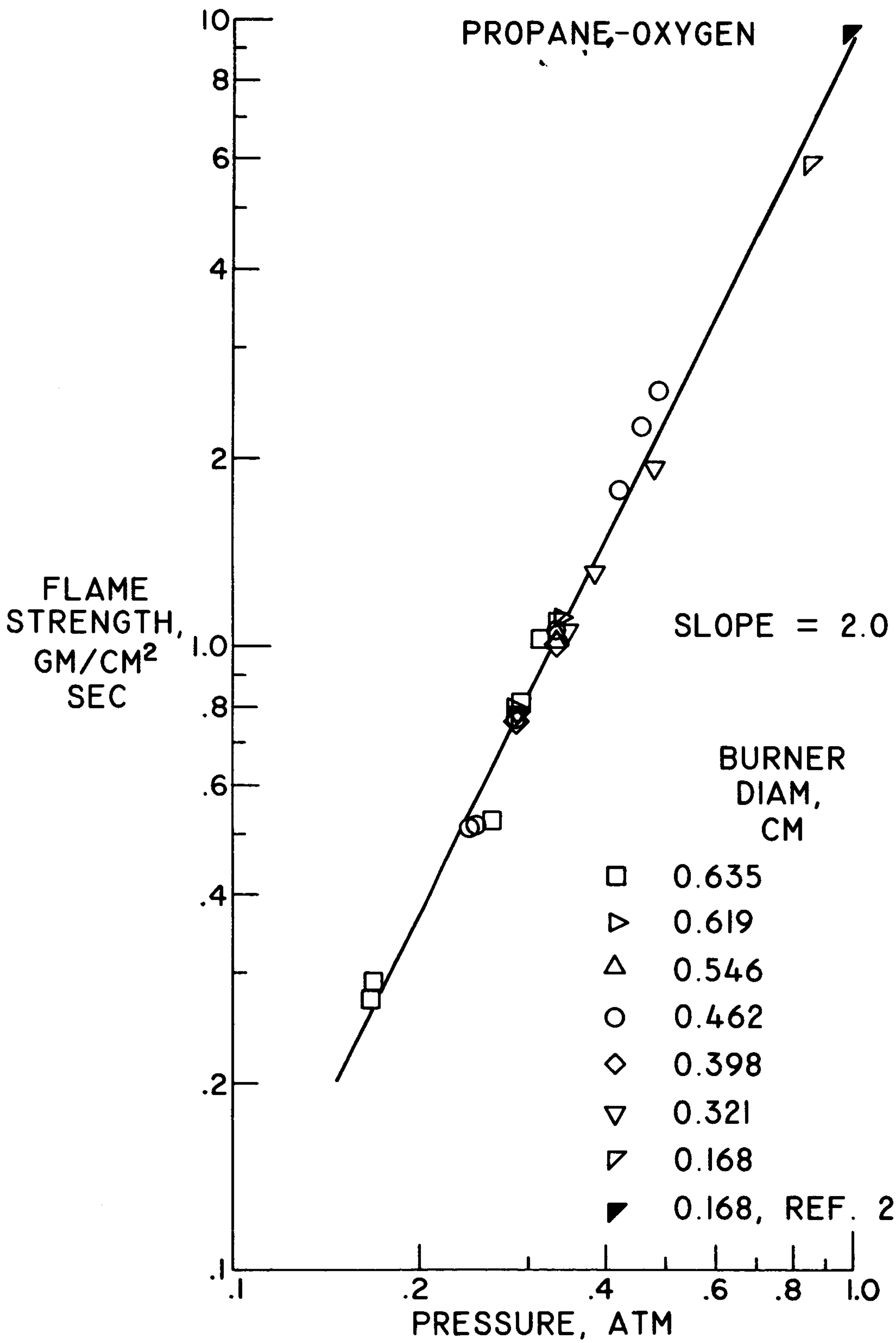

Fig. 3. Pressure dependence of flame strength.