LEAN LIMIT PHENOMENA

C. K. Law
Northwestern University
Evanston, Illinois 60201

The influence of stretch and preferential diffusion on premixed flame extinction and stability have been investigated via two model flame configurations, namely the stagnation flame and the bunsen flame. The results are separately summarized in the following.

(1) Extinction and Stability of Stretched Premixed Flames in the Stagnation Flow

Using a counterflow burner and a stagnation flow burner with a water-cooled wall, the effect of downstream heat loss on the extinction of a stretched premixed flame has been systematically investigated for lean and rich propane/air and methane/air mixtures. Based on results of the concentration limits and flame separation distances at extinction, it is demonstrated that, in accordance with theoretical predictions, extinction by stretch alone is possible only when the deficient reactant is the less mobile one. When it is the more mobile one, downstream heat loss or incomplete reaction is also needed to achieve extinction. A variety of unstable flame configurations have been observed; the mechanisms for their generation and sustenance are discussed.

(2) Opening of Premixed Bunsen Flame Tips

The local extinction of bunsen flame tips and edges of hydrocarbon/ air premixtures has been experimentally investigated using a variety of burners. Results show that, while for both rich propane/air and butane/ air mixtures tip opening occurs at a constant fuel equivalence ratio of 1.44 and is therefore independent of the intensity, uniformity, and configuration of the approach flow, for rich methane/air flames burning is intensified at the tip and therefore opening is not possible. These results substantiate the concept and dominance of the diffusional stratification mechanism in causing extinction, and clarify the theoretical predictions on the possible opening of two-dimensional flame wedges.

(3) Publications

(a) "Lean-Limit Extinction of Propane/Air Mixtures in the Stagnation-Point Flow," by C. K. Law, S. Ishizuka, and M. Mizomoto, Eighteenth Symposium on Combustion, pp. 1791-1798 (1981).

(b) "Effects of Heat Loss, Preferential Diffusion, and Flame Stretch on Flame-Front Instability and Extinction of Propane/Air Mixtures," by S. Ishizuka, K. Miyasaka, and C. K. Law, Combustion and Flame, Vol. 45, pp. 293-308 (1982).

(c) "On the Opening of Premixed Bunsen Flame Tips," by C. K. Law, S. Ishizuka, and P. Cho, Combustion Science and Technology, Vol. 28, pp. 89-96 (1982).

(d) "On Stability of Premixed Flame in Stagnation-Point Flow," by G. I. Sivashinsky, C. K. Law, and G. Joulin, Combustion Science and Technology, Vol. 28, pp. 155-159 (1982).

(e) "An Experimental Study of Extinction and Stability of Stretched Premixed Flames," by S. Ishizuka and C. K. Law, to appear in Nineteenth Symposium on Combustion, 1983.

OBJECTIVES

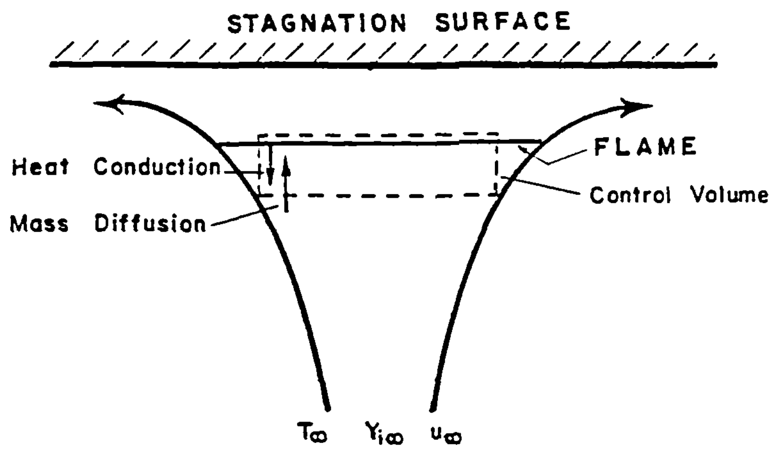
- TO STUDY EFFECTS OF
  1. PREFERENTIAL DIFFUSION ($Le \neq 1$)
  2. AERODYNAMIC STRETCHING (FLOW NON-UNIFORMITY, UNSTEADINESS, AND FLAME CURVATURE)
  3. DOWNSTREAM HEAT LOSS
- ON
  - A. FLAME EXTINCTION
  - B. FLAME-FRONT INSTABILITY

METHODOLOGY

1. PREFERENTIAL DIFFUSION EFFECTS STUDIED BY USING

	METHANE/AIR	PROPANE/AIR
LEAN	$Le < 1$	$Le > 1$
RICH	$Le > 1$	$Le < 1$

2. AERODYNAMIC STRETCHING STUDIED BY USING STAGNATION FLOW WHICH HAS WELL-DEFINED VELOCITY GRADIENT
3. DOWNSTREAM HEAT LOSS STUDIED BY USING
   - (a) STAGNATION FLOW WITH WATER-COOLED SURFACE
   - (b) SYMMETRICAL COUNTERFLOW



Schematic of Stagnation-Point Flow Illustrating the Directions of Heat and mass Diffusion.

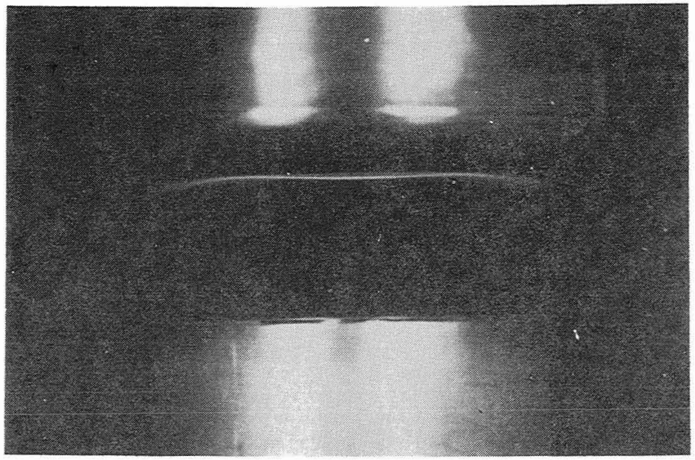
EXTINCTION MECHANISMS

Le > 1 Flames

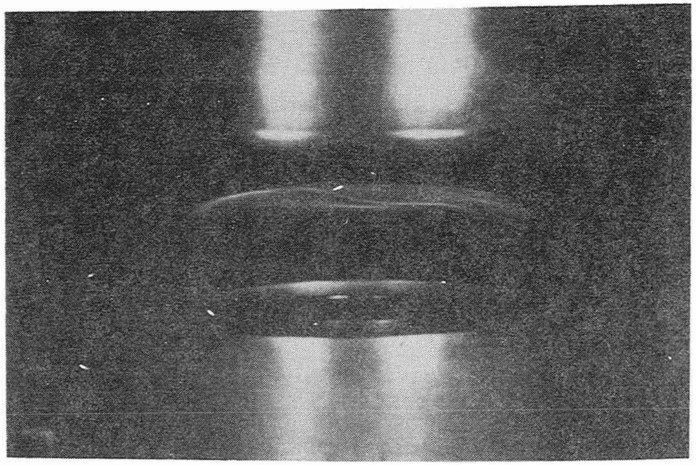
1. STRETCH ALONE CAN CAUSE EXTINCTION; DOWNSTREAM HEAT LOSS MINIMAL EFFECT
2. INCREASING STRETCH DECREASES FLAME TEMPERATURE
3. AT EXTINCTION, FLAME LOCATED AWAY FROM STAGNATION SURFACE
4. AT EXTINCTION, DEFICIENT REACTANT COMPLETELY CONSUMED

Le < 1 Flames

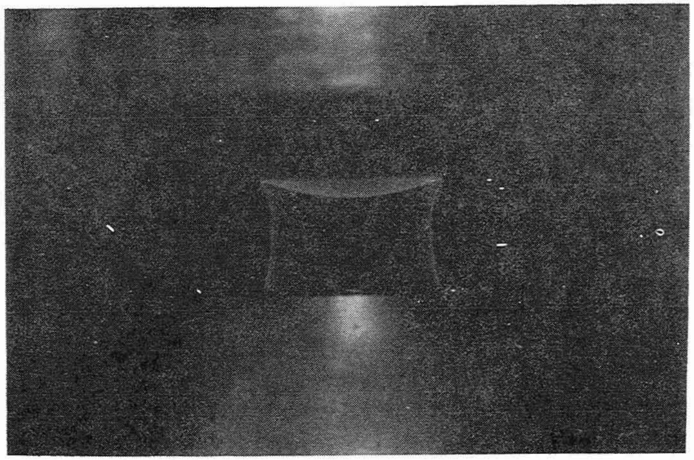
1. INCREASING STRETCH INCREASES FLAME TEMPERATURE, THEREFORE STRETCH ALONE CANNOT CAUSE EXTINCTION
2. EXTINCTION CAN BE ACHIEVED THROUGH
   (a) DOWNSTREAM HEAT LOSS, WITH FLAME AWAY FROM WALL
   (b) INCOMPLETE COMBUSTION WITH FLAME AT WALL



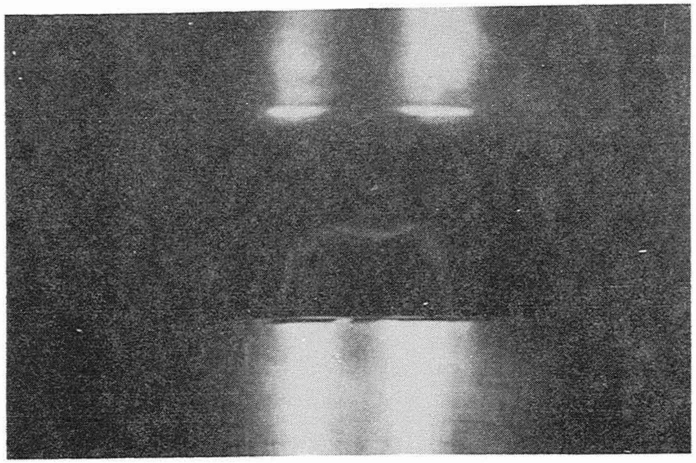
(a)



(b)

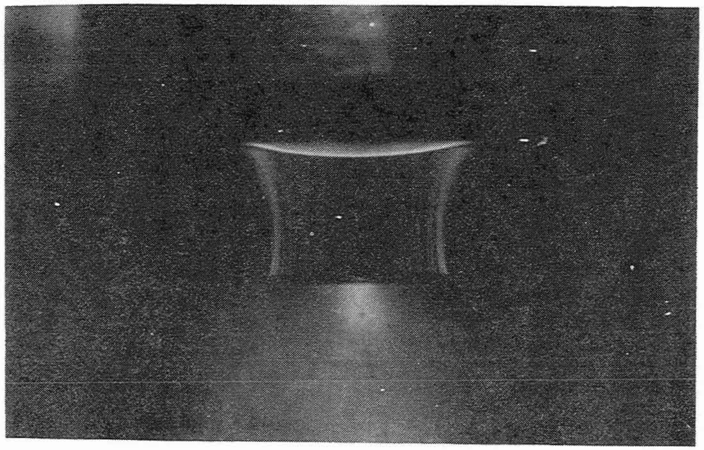


(c)

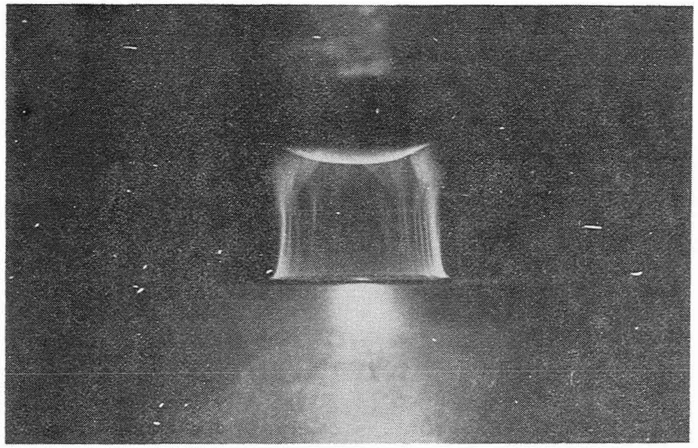


(d)

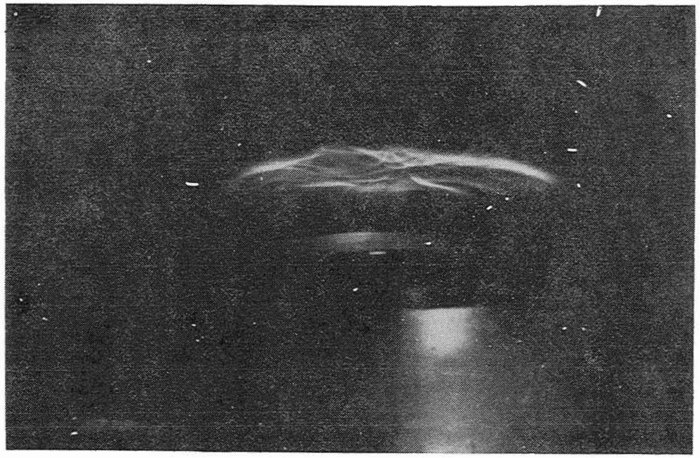
Various Flame Configurations for Propane/Air Mixtures in the Stagnation-Point Flow (See Publication No. b)



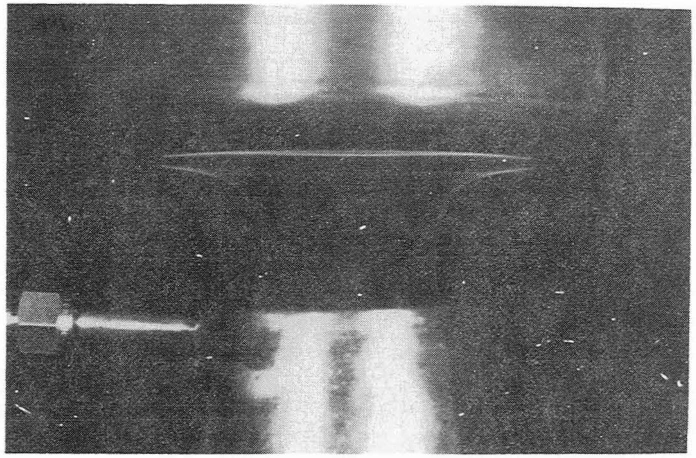
(e)



(f)

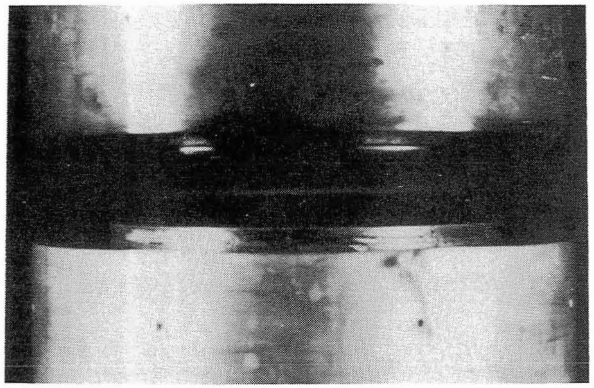


(g)

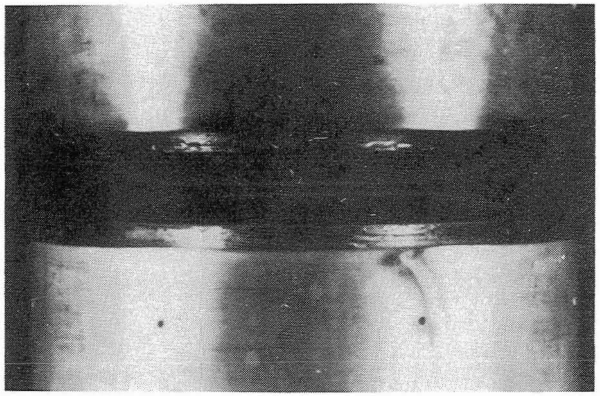


(h)

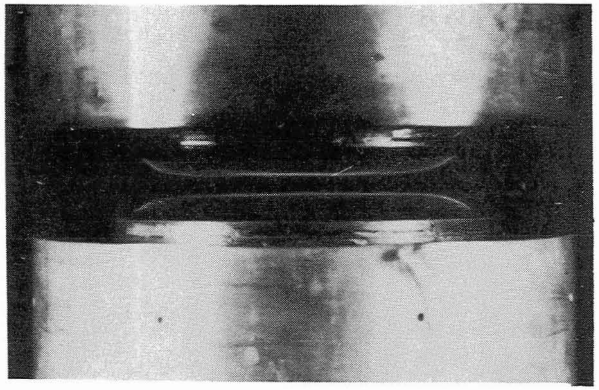
Various Flame Configurations for Propane/Air Mixtures
in the Stagnation-Point Flow (See Publication No. b)



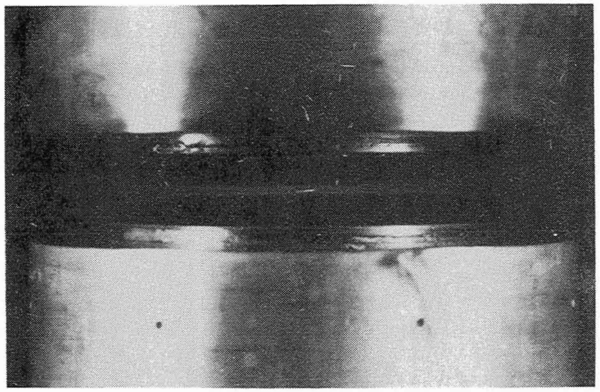
(a)



(b)

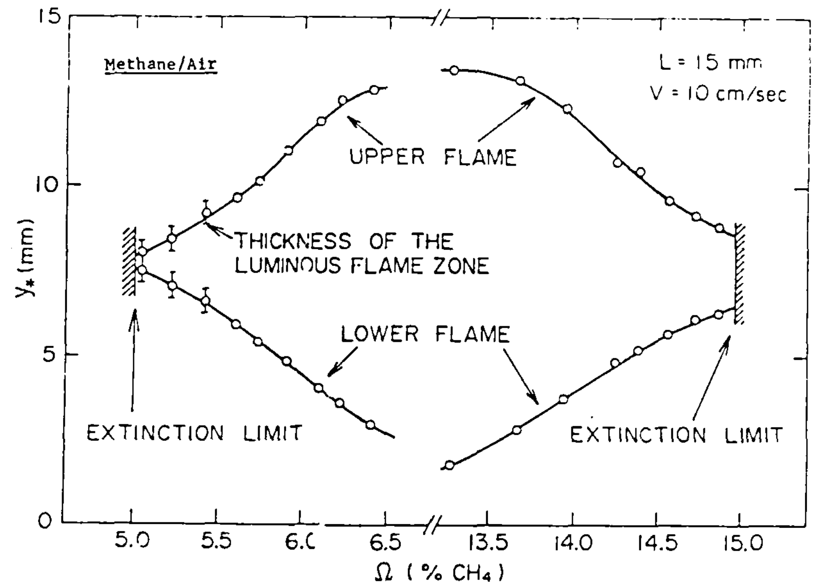


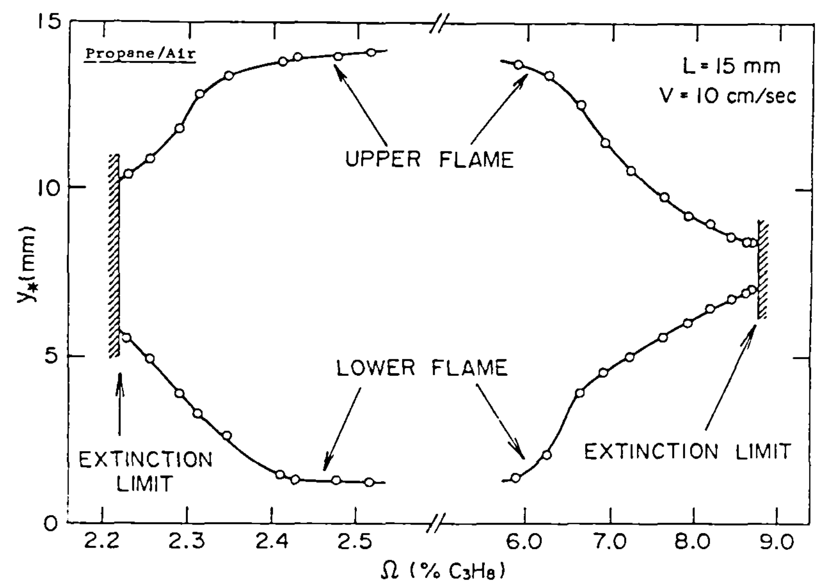
(c)



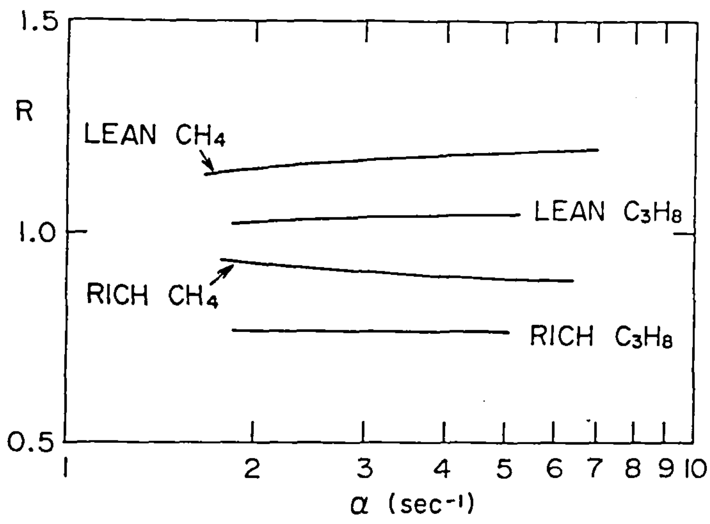
(d)

Flame Separatedness at Extinction in the Counterflow Geometry. (a) Lean Methane/Air, (b) Rich Methane/Air, (c) Lean Propane/Air, (d) Rich Propane/Air (See Publication No. e)





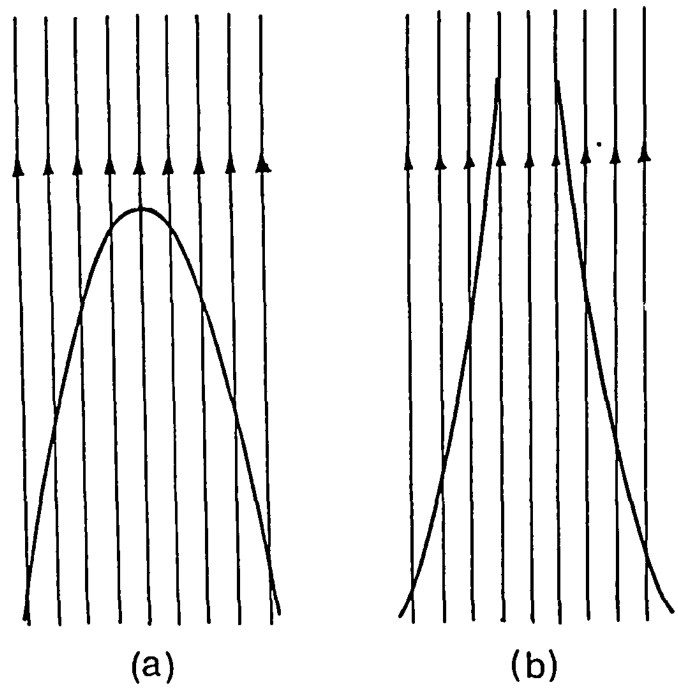
Location of the Binary Flames Illustrating Flame Separatedness at Extinction



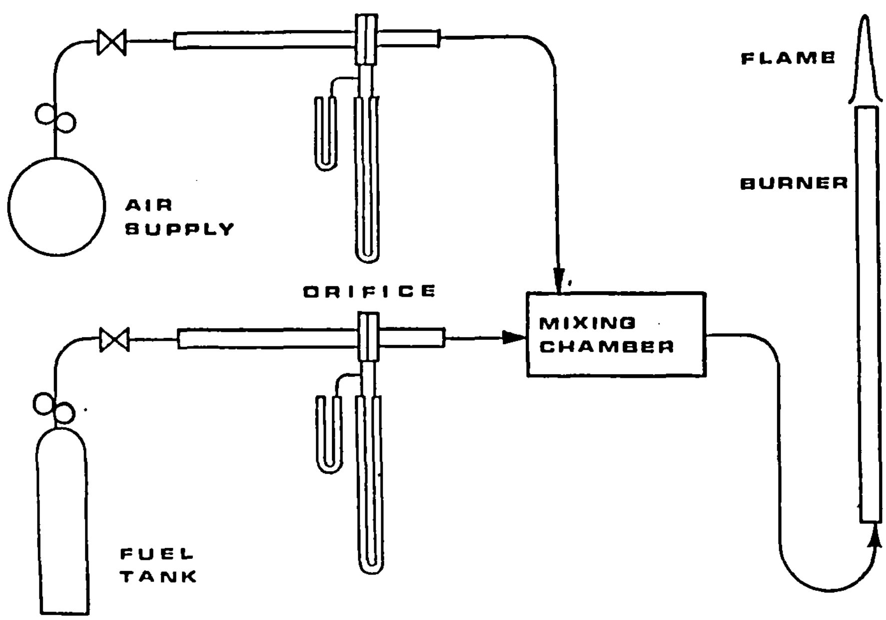
Ratio of the Extinction Concentration Limits with and without Downstream Heat Loss

Author	Method	Definition	% Methane		% Propane	
			Lean	Rich	Lean	Rich
Zabetakis	Propagating flame (tube)	Extinction	5.0	15.0	2.1	9.5
Andrews and Bradley	Propagating flame (vessel)	Extinction	4.5	15.5	-	-
Egerton and Thabet	Flat flame	Burning velocity	5.1	-	2.01	-
Sorenson, Savage, and Strehlow	Tent flame	Cone angle	4.0	15.0	-	-
Yamaoka and Tsuji	Double flame	Flame location	4.7	15.3	-	-
Ishizuka and Law	Binary flame	Extinction	4.8	15.8	2.0	9.7

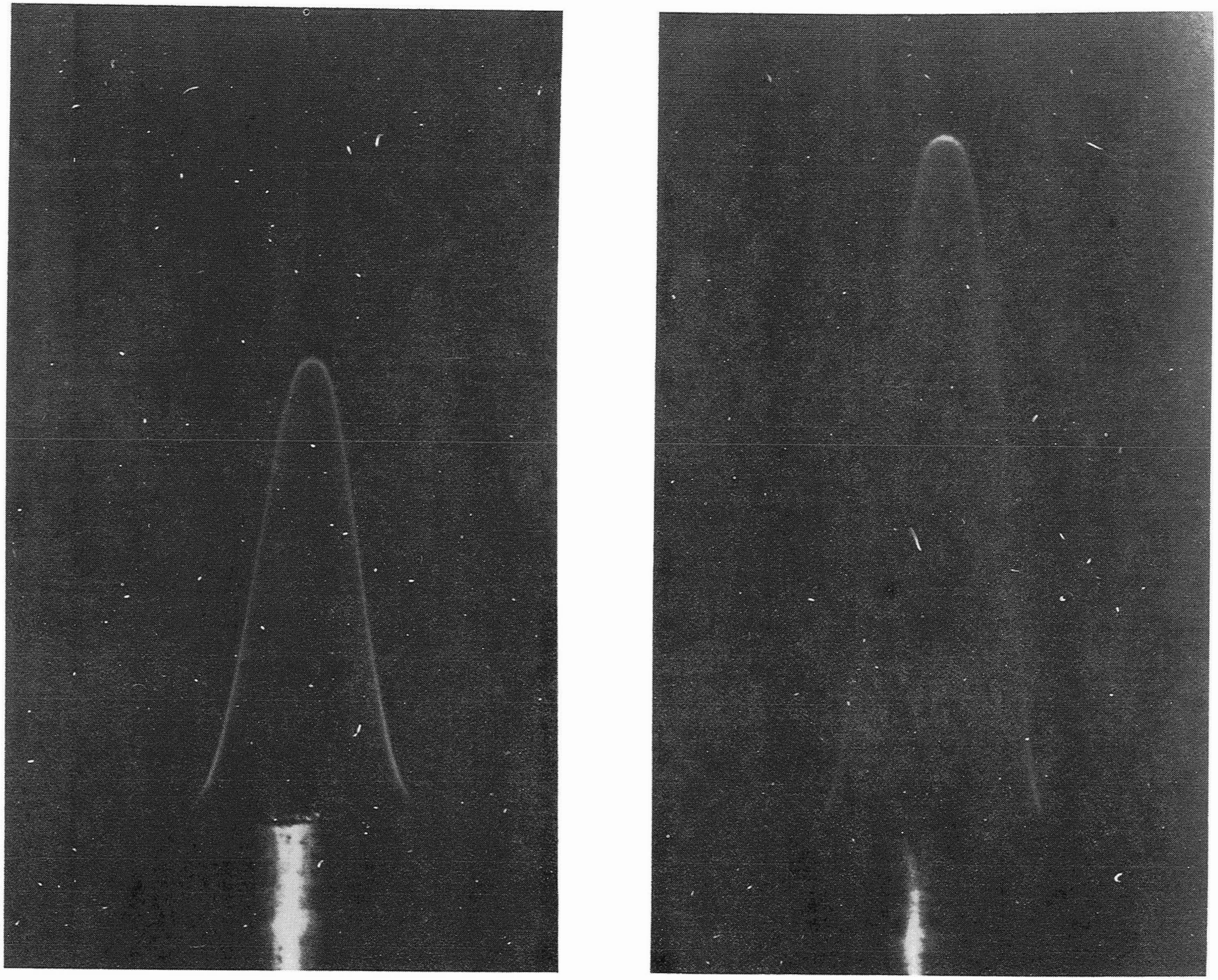
Comparison of the Flammability Limits of Methane/Air and Propane/Air Mixtures Determined by Different Methods



Schematic of Closed and Open Bunsen Flame Tips

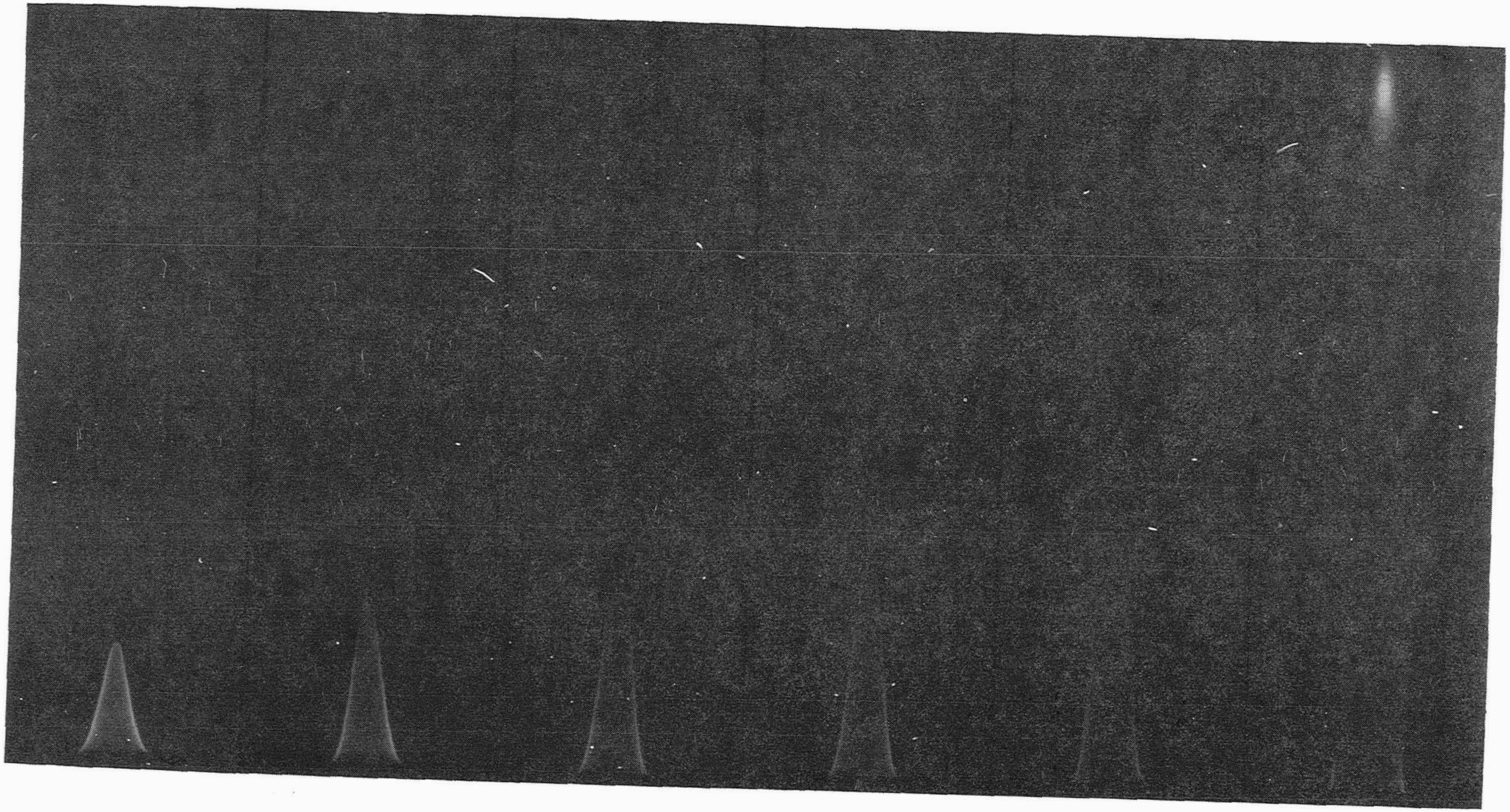


Set-Up of the Bunsen Flame Experiment



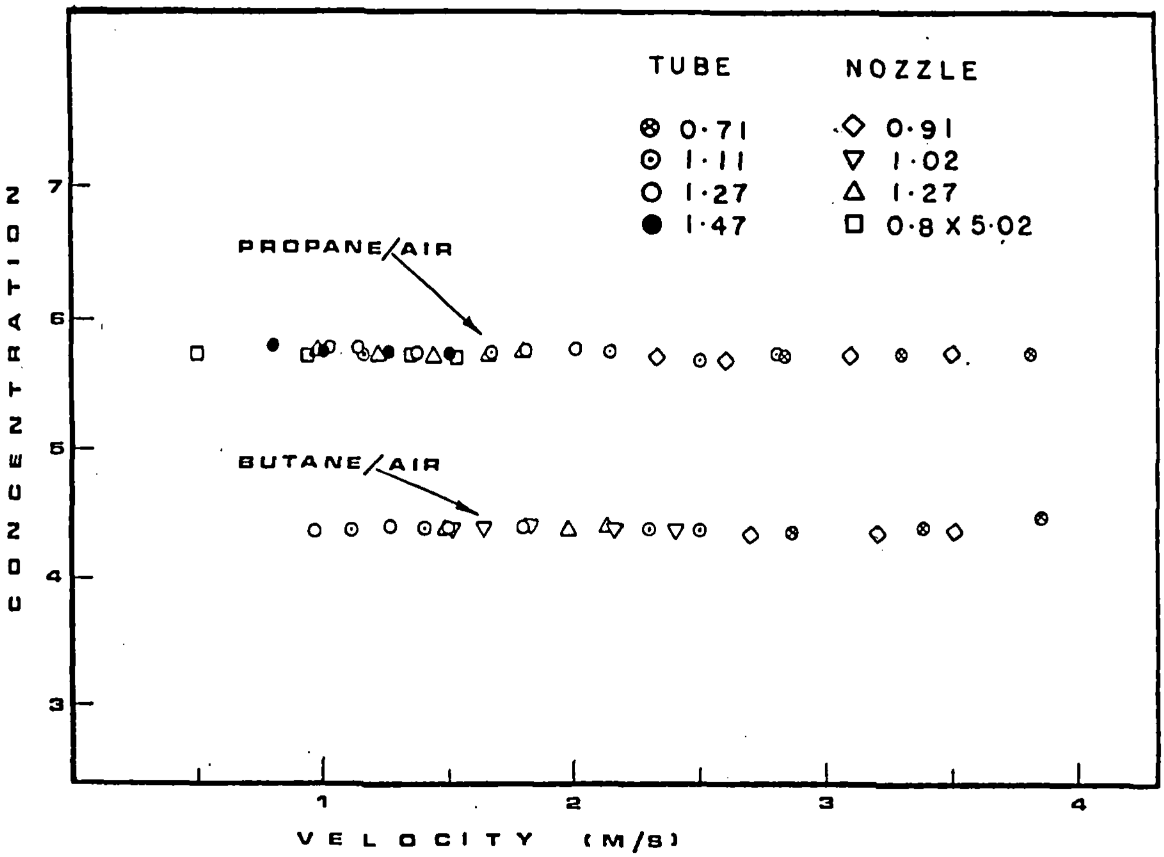
(a) (b)

Tip Intensification of Rich Methane/Air Bunsen Flame with Increasing Methane Concentration (See Publication No. c)



(a) (b) (c) (d) (e) (f)

Tip Opening of Rich Propane/Air Bunsen Flame with Increasing Propane Concentration (See Publication No. c)



Fuel Concentrations at Tip Opening as Function of Flow Velocity for a Variety of Burners