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A Bifurcated Diffusion Flame

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1 Introduction

One approach to the study of turbulent diffusion flames is to study the response of laminar flames to specific perturbations. In the course of examining the response of a simple jet diffusion flame to axial acoustic perturbations, an unusual flame phenomenon has been observed. At specific excitation frequencies the flame can be driven to bifurcate into a central jet and one or two side jets as shown in Figures 1a and 1b. A perpendicular mirror view is also shown. The bifurcation is accompanied by a partial detachment of the flame from the nozzle exit, a shortening of the flame by a factor of two, and a change from the common yellow color of soot radiation to a clear blue flame. The corresponding unexcited flame is shown in Figure 1c.

The ability to control soot production or product species in a diffusion flame using an open loop forcing technique is potentially quite useful.

While the study of perturbed diffusion flames is an active topic (Schadow et al. 1990; T.Y. Chen et al. 1993; L.D. Chen et al. 1992; Lasheras et al. 1992; Chao and Jeng 1992) this bifurcating flame phenomenon has not been reported, to our knowledge. However, a similar phenomenon was observed by Tyndall (1875) who studied the response of 'naked' (unconfined) gas jet flames to sound: "A long flame may be shortened and a short one lengthened, according to circumstances, by sonorous vibrations. The flame shown in Fig. 125 is long, straight, and smoky; that in Fig. 126 is short, forked and brilliant. On sounding the whistle, the long flame becomes short, forked and brilliant, as in Fig. 127; while the forked flame becomes long and smoky, as in Fig 128. As regards, therefore, their response is the complement of the other." These figures are reproduced in Figure 2.

The analysis of this phenomenon is at an early stage. The preliminary results presented here are the conditions known to produce the bifurcation, including the range of flow rates, forcing frequencies and amplitudes, and a brief investigation of the effect of nozzle shapes and lengths.

2 Experimental Description

The experiment consists of an axisymmetric methane jet formed by a short length of 4.5 mm inner diameter stainless steel tubing. A schematic is shown in Figure 3. The pipe is connected to a large cylindrical plenum chamber surrounding a bass reflex loudspeaker enclosure. Three pipe lengths have been used: 8.23, 11.6, and 24.9 cm. A range of flow rates from 13 ml/s to 70 ml/s have been studied, and for these flow rates the pipe flow is not expected to be fully developed. The Reynolds number, based on pipe diameter, ranged from approximately 240 to 1000. The flow rate was measured with a rotameter.

The excitation was provided by a 16.5 cm 8 ohm cone type loudspeaker (Alpine model 6267GX), driven by a Yamaha MX-80 200 watt amplifier, driven in turn by a sine wave function generator (HP 651B). The flame was observed as the forcing frequency was varied from 40 to 1000 Hz. The response of the speaker system decreased rapidly above 1 kHz.

The flame was recorded using a Nikon F4 35mm camera with ISO 400 Kodak Tmax and Ektachrome films, at shutter speeds from 1/60th to 1/15th sec. These photographs can be considered time averaged with respect to the forcing frequency. Both color and b/w video images were also recorded.

3 Results

The bifurcation behavior was observed at all flow rates ranging from the lowest measurable flow rate, 10 ml/s, to a flow rate just above that of lift-off, 95 ml/s.

The behavior ocurred at 246 +/- 20 Hz. This frequency range was found to be insensitive to the flow rate. It was also found to be independent of forcing amplitude and nozzle length. Bifurcation was seen at other frequencies up to 750 Hz, but the behavior was not repeatable. With an earlier configuration using a different manufacturer's loudspeaker in the same enclosure, and a marginally longer plenum section, bifurcation was seen at specific higher frequencies which were dependent on nozzle length. Slight modifications were made to the plenum to facilitate speaker replacement, since they are often driven to failure. Since then, bifurcation has only been found repeatably near 246 Hz. This frequency is close to 240 Hz, a standing wave mode of the plenum using the speed of sound in pure methane and assuming 1.5 wavelengths in the plenum, that is, one closed and one open end. The Helmholtz resonance mode for the nozzle and plenum combination was 4 Hz, well below any examined frequency.

Outside of these frequencies the flame appeared to be an unremarkable transitional diffusion flame, although the flame height showed some sensitivity to the excitation frequency, particularly at low flow rates.

The amplitude of forcing at 246 Hz required to cause bifurcation varied with flow rate, with the lower flow rates being more sensitive to forcing. Details of the bifurcation shape also varied with flow rate and forcing amplitude. A mode map showing these sensitivities was determined for three flow rates, 14, 34 and 61 ml/s, and is given in Figure 4.

At the lowest flow rate and highest excitation level, with 35 volts peak to peak (Vpp) into the speaker, the flame formed two or three distinct co-planar jets, hopping between these bi- and trifurcated modes. The flame was pure blue, with no visible soot emission. At a moderate forcing level, the bifurcated mode dominated. The flame also emitted a hissing noise, audible even above the acoustic forcing. During the bifurcation, the position of the side jet was sometimes stable and insensitive to room air currents, and at other times the side jets would revolve slowly or rapidly.

At a lower forcing level, 15 Vpp, the flame formed a 'tri-mode', with three bulges equispaced azimuthally. No yellow soot emission was observed, even at the tips of the bulges. At lower forcing levels, the flame formed a 'monomode' in which the side jet was not clearly delineated, although the flame emission was pure blue, and the flame height was half of the unexcited jet. This mode was not stable and would give way to the unexcited, sooty jet flame mode. It was sensitive to additional perturbations, such as gentle blowing or hand-waving, and could be induced back to the monomode. Below 6 Vpp such perturbations were not effective and often resulted in flame extinguishment.

At an intermediate flow rate (34.2 ml/s) the flame was again bi- or trifurcated at the highest forcing levels. This flame exhibited some yellow soot radiation at the tips of the blue flames. As the forcing level was decreased to 24 Vpp, the monomode became predominant, with a clear bifurcation seen around 10% of the time. As the forcing level was lowered further, the bifurcated mode dominated again, but became intermittent with the unexcited mode. Below 13 Vpp external perturbation was required to cause the bifurcated mode, which would last a few seconds before reverting to the sooty mode.

At the highest forcing level, the bifurcation persisted as the flow rate was increased until 61.3 ml/s. At that flow rate and lower excitation levels, external perturbation was effective at inducing bifurcation. Spontaneous bifurcation decreased as the excitation level decreased until 16 Vpp. Below that level perturbation was required to cause bifurcation. The minimum forcing level at which bifurcation could be obtained for this flow rate was 12.5 Vpp.

At flow rates above 81 ml/s the flame was a lifted, turbulent non-premixed flame. No combination of acoustic forcing and external perturbation could induce a clear bifurcation, but the monomode could be excited spontaneously.

Several lip conditions of the stainless steel tubing forming the nozzle were investigated. It was quickly determined that a nicely machined, flat lip such as that in Figure 5a resulted in a flame that would not bifurcate under any conditions. On the other hand, a crude cut made with a dull tubing cutter, as shown in Figure 5b, is able to produce a bifurcating flame under the wide range of conditions described above. The significant burr seems to be responsible for the flame behavior. It is interesting to note that although the burr was not uniform, with the inner diameter ranging from 2.8 to 3.2 mm, the side jets exhibited no spatial preference for any feature of the burr.

Three nozzle lengths were used. The flame behavior was identical for the two shorter lengths, 8.2 and 11.6 cm. The bifurcations ocurred at the same frequencies, but seemed to require higher excitation levels with the longest nozzle of 24.9 cm. This effect was not quantified, however.

4 Discussion

Although Tyndall's figure (Figure 2) bears a striking resemblance to our bifurcated flame, several details of his description differ from our results. Our bifurcated flame is not 'brilliant', in fact, it gives off little light, and is closer in description to another of Tyndall's 'sensitive' flames, "a pale and almost non-luminous residue of it alone remaining." Also, Tyndall's work was inspired by that of Le Conte, who found that the unconfined flame was not sensitive unless the gas pressure was almost high enough to cause 'flaring', presumably a transition to a turbulent flame. In contrast, the present results indicate that flames with a lower flow rate require less excitation than one close to lift-off. Finally, Tyndall reports that the flames were more sensitive to frequencies ranging from 1.6 kHz to 3.2 kHz, while ours responded to much lower frequencies. Thus we cannot conclude that Tyndall's phenomenon is the same as the observed bifurcated flame.

The fluid mechanics responsible for this phenomenon have not yet been determined, since this work is at an early stage. However, there are several possibilities for driving mechanisms. Nonreacting jets have been observed to bifurcate by Juvet and Reynolds (1990) who have studied the combined effect of helical and axial excitation. Due to the high forcing levels, vibratory modes in the plenum/nozzle structure could produce multiple excitation modes. However, since the most effective frequency was invariant with nozzle length, this possibility seems less likely.

Since the density of methane is approximately one half that of air, the possibility arises that the observed behavior is an effect of an absolute instability of the fuel jet, as described by Monkewitz, Becher, Barsikow and Lehmann (1990). Under appropriate shear layer and density ratio conditions, a heated jet has been observed to throw out 'side jets'. These jets have been attributed to an absolute instability of the jet. An absolute instability produces flow perturbations which, once excited, do not convect downstream with the flow. However, such instabilities are generally susceptible to *low* amplitude perturbations, unlike the observed flame perturbations. Still, another test for absolute versus convective instabilities is that the amplitude of the flow perturbations from an absolute instability is insensitive to forcing level, while the amplitude of a perturbation from a convective instability is expected to be linear with excitation amplitude. In the present flame, the size of the side jets are only weakly dependent on the forcing level, once they are excited at all. Thus an absolute instability mechanism may be responsible for the bifurcated phenomenon.

A third possible mechanism is suggested by the behavior of separated flow in contractions. The flow is bistable, attaching to one side or another. Such behavior may be responsible for the split flames.

5 Conclusion

An unusual flame phenomenon in which an unconfined methane diffusion flame splits into two or three side jets has been observed under a range of sinusoidal axial acoustic forcing conditions. A high level of forcing is required for continuous bifurcation, although lower levels are capable of producing the effect for short periods of time if additionally perturbed. The behavior was observed at a wide range of flow rates, but not past the lift-off stage. The bifurcations ocurred over a narrow forcing frequency range, and only with specific nozzle lip conditions.

Future investigation is planned to include phase locked flow visualization to determine the state of the jet shear layer leading to the bifurcated flame under reacting and nonreacting conditions. The level of the acoustic perturbation at the nozzle exit will be quantified with pressure transducers. Velocity measurements with LDA or PIV will be considered, and the product gases will be analyzed.

6 Acknowledgements

Our thanks go to Matt Cuddy, Jeff Cloutier, Russ Eckman, Brooke Gebre-Mariam, and Tim Saffell, the students who built the prototype combustor and made the first tests. This work is supported by a grant from the Council on Research and Creative Work, of the University of Colorado, Boulder.

7 References

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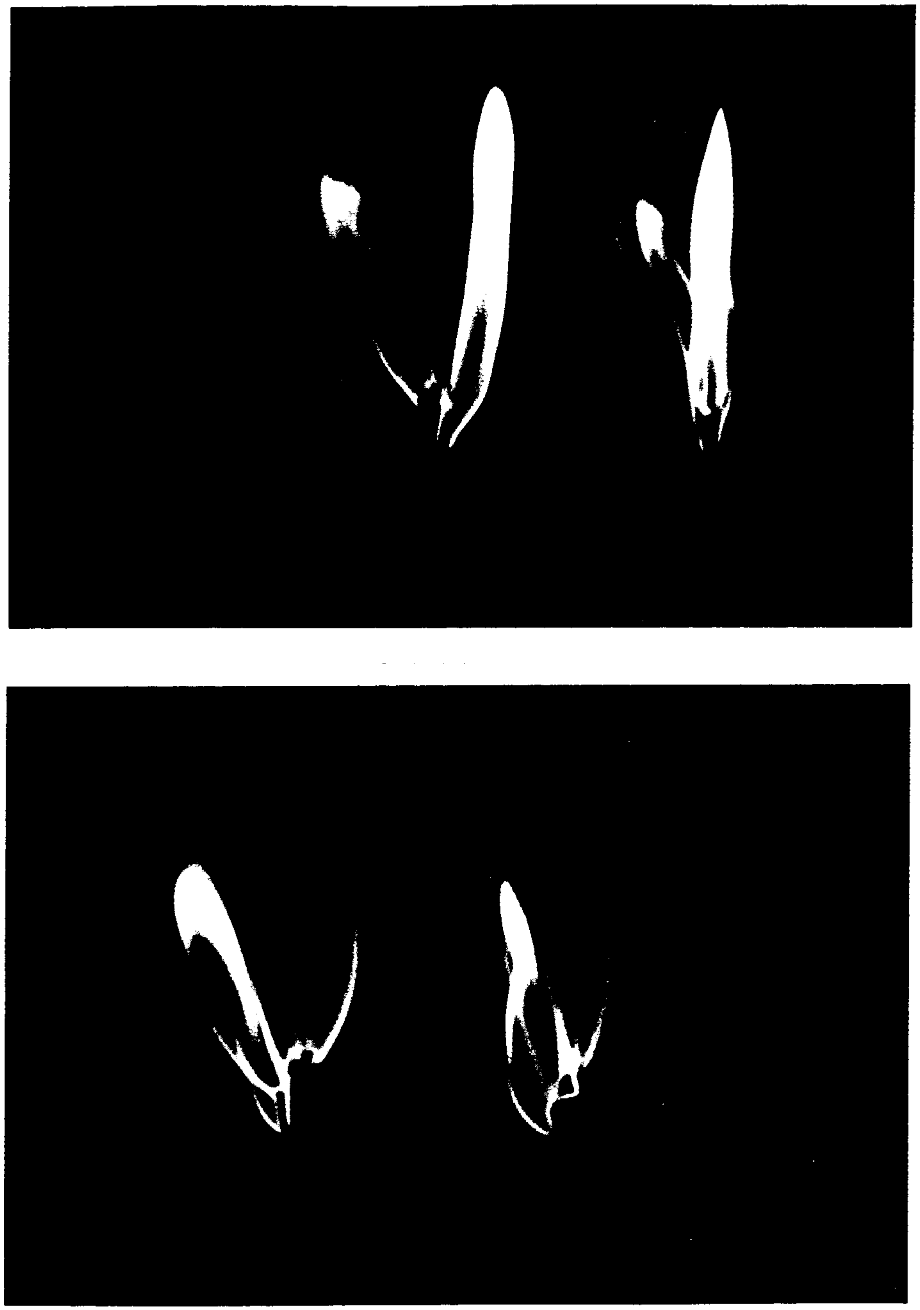

Figure 1 a and b. Methane jet flame 32.2 ml/sec forced at 240 Hz, 24 volts peak-peak

Figure 1 c. Unexcited methane jet flame, 32.2 ml/sec.

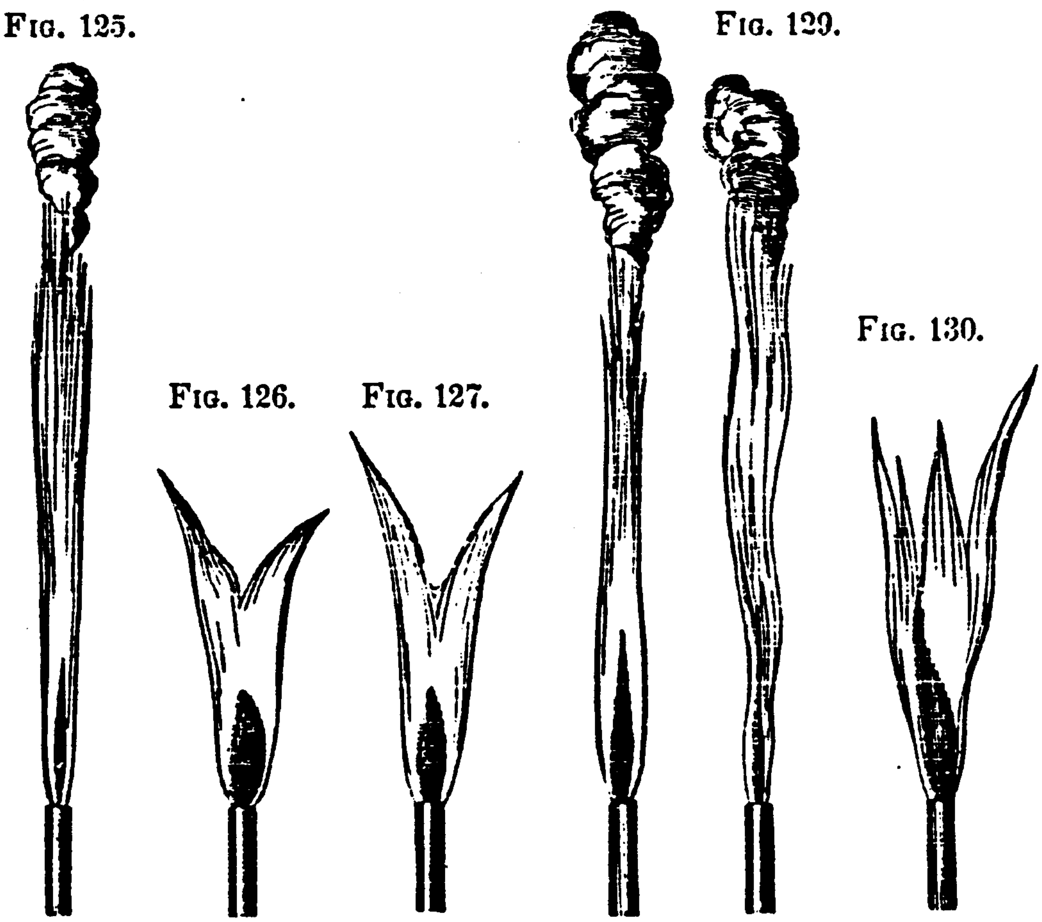

Figure 2: Acoustically excited and unexcited jet flames, from Tyndall's *Sound,* 1875.

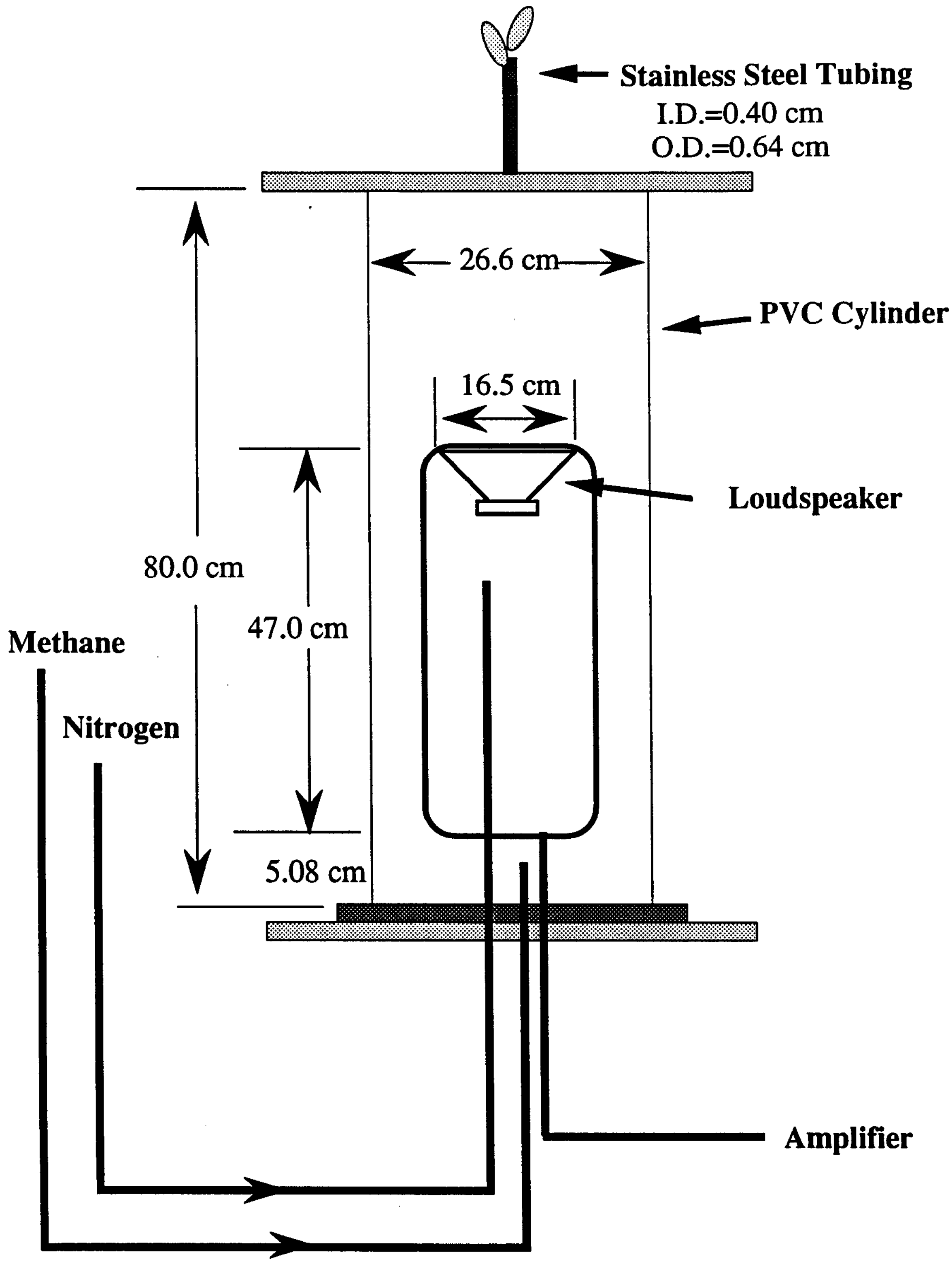

Figure 3: Experiment Schematic

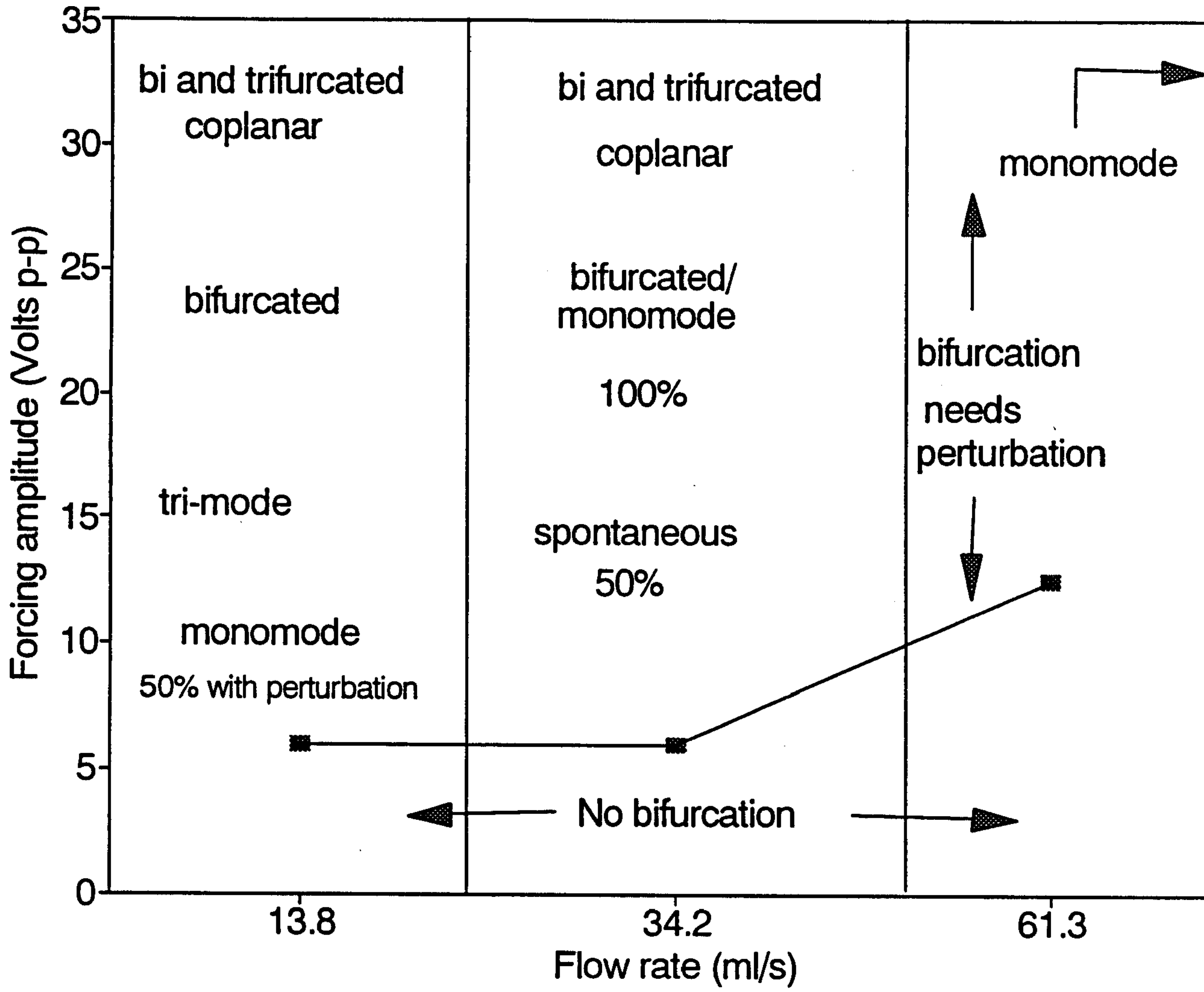

Figure 4: Mode map

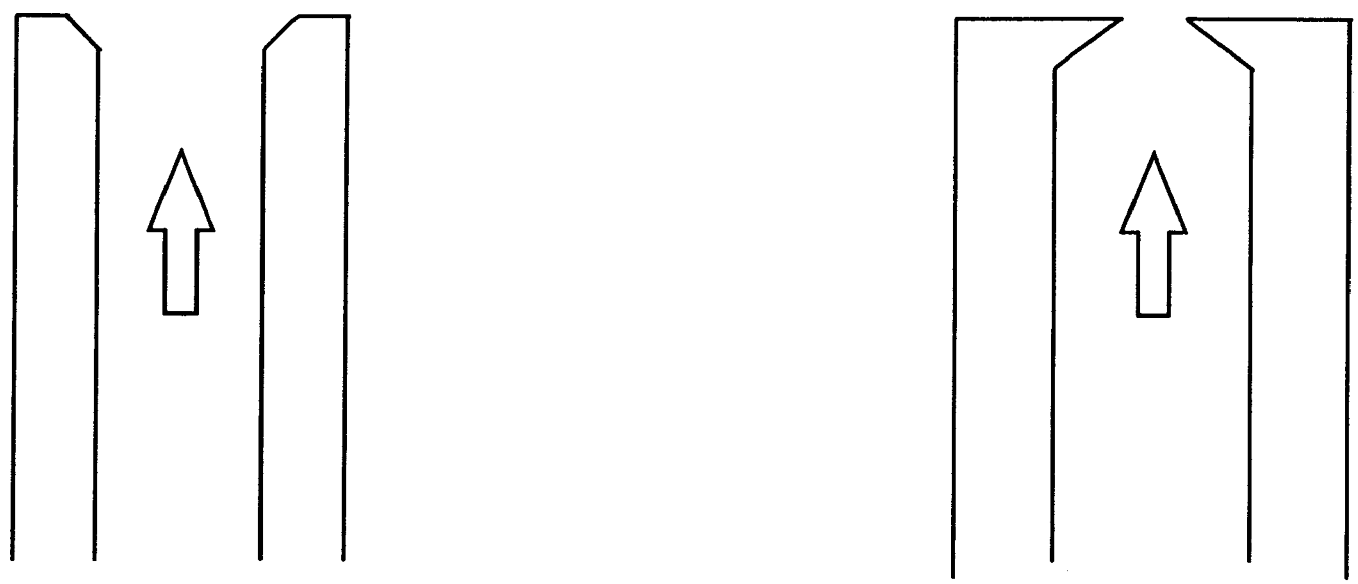

Figure 5

a) Machined nozzle lip. Does not cause bifurcation.

b) Crude cut with burr. Causes bifurcation.

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INVITATION

The 1994 Spring Meeting of the Western States Section of the Combustion Institute will be held **21 & 22 March 1994** at the University of California at Davis, California under the sponsorship of the University of California at Davis.

CALL FOR PAPERS

Technical papers are solicited on aspects of combustion relating to Incineration and Health Effects, Turbulent Sprays, Material Synthesis, Combustion in Practical Systems, and General Topics. Submitted papers may cover a broad range of topics from fundamental studies of combustion phenomena to practical applications of combustion technology.

Papers on both basic and applied research are sought. Papers from industrial organizations are strongly encouraged.

Please note that presentation of a paper at this meeting does not constitute a publication.

Deadlines: Prospective authors should submit an Extended Abstract of at least 500 words by **January 3, 1994** and the complete paper by **March 18, 1994**. One copy of the Abstract should be sent to each of the following officers:

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150 preprint copies of accepted papers are due at the University of California at Davis no later than **March 18, 1994**. Send to Prof. Ian M. Kennedy, Dept. of Mechanical Engineering, University of California at Davis, Davis, CA 95616, Phone: (916) 752-2796; Fax: (916) 752-4158.

Presentation of accepted papers is contingent upon having 150 preprints of the full paper available at the meeting.

PROCEDURE FOR REVIEW AND FORMULATION OF THE PROGRAM

Acceptance is based upon review of the Extended Abstract. Separate copies of the abstract must be sent to the persons named above. Abstracts are required by **January 3, 1994** to allow sufficient time to organize the technical sessions. Decisions of the Papers Review Committee on acceptances will be transmitted to the authors by **February 1, 1994**. Complete papers must be submitted by **March 18, 1994** as evidence that the paper has been composed, internally reviewed, and cleared by any requisite external reviewing agency, and will indeed be available for presentation.

REGISTRATION FEES, AWARDS, AND PREPRINT SETS

The meeting preregistration fee is $100.00 for members of the Combustion Institute, $140.00 for nonmembers, and $20.00 for students with suitable identification. Preregistration deadline is **March 11, 1994**. Preregistration checks should be made payable to the **Western States Section/The Combustion Institute** and sent to Prof. Ian M. Kennedy, Dept. of Mechanical Engineering, University of California at Davis, Davis, CA 95616. Registration at the door is $140.00 for CI members and $180.00 for nonmembers. Nonmembers may elect to have the $40.00 differential applied to membership in the Combustion Institute. An award of $150.00 will be made to each student who presents a paper before the Section, excluding students affiliated with local institutions. **Please indicate the author who will present the paper and his or her student status on the abstract.** Preprint sets are provided to paid conference attendees. After the meeting, preprints will be available from the Secretary for $100.00 per set, and $150.00 foreign. Make checks payable to: **Western States Section/The Combustion Institute.** Send to Dr. Jay O. Keller, Secretary, WSS/CI.

Abstracts Due January 3, 1994 **Preregistration Due March 11, 1994** **Papers Due March 18, 1994**

TUESDAY, March 22, 1994

Morning session 3A: **Material Synthesis**; Chair: **Ralph Aldredge III**, University of California at Davis

8:30	94-016	Gas Phase Kinetics of High Temperature $Ti/O/H/C$ Chemistry, **J. S. McFeaters, P. Schwerdtfeger, R. L. Stephens, & M. Liddell**, Computational Materials Science & Engineering Research Center, School of Engineering, Auckland University, Auckland, New Zealand.
8:55	94-017	Finite Element Modeling of Gas-Solid SHS Reactions in the $Zr + O_2$ System, **K. H. Ewald & Z. A. Munir**, Department of Chemical Engineering & Materials Science, University of California at Davis, Davis, CA.
9:20	94-018	Field-Assisted Self-Propagating Combustion Synthesis, **A. Feng & Z. A. Munir**, Department of Chemical Engineering & Materials Science, University of California at Davis, Davis, CA.
9:45	94-019	A Parametric Study of Diamond Growth in Low Pressure Premixed Flames, **J. S. Kim & M. A. Cappelli**, High Temperature Gasdynamics Laboratory, Department of Mechanical Engineering, Stanford University, Stanford, CA.
10:10		Break
10:40	94-020	Kinetics Issues in Diamond CVD Growth Modeling, **G. P. Smith, D. M. Golden, & J. B. Jeffries**, Molecular Physics Laboratory, SRI International, Menlo Park, CA.
11:05	94-021	Streamline Chemistry in Arc Heated Plasma Reactors for Diamond Chemical Vapor Deposition, **C. D. Moen & H. A. Dwyer**, Department of Mechanical & Aeronautical Engineering, University of California at Davis, Davis, CA.
11:30	94-022	Diamond Film Deposition in Low-Pressure Flat Flames, **N. G. Glumac, H. S. Shin, & D. G. Goodwin**, Division of Engineering & Applied Science, California Institute of Technology, Pasadena, CA.
11:55	94-023	Laser-Induced Fluorescence of CH in DC-Arc-Jet Plasmas, **J. B. Jeffries, G. A. Raiche, & M. S. Brown**, Molecular Physics Laboratory, SRI International, Menlo Park, CA.
12:20		Lunch

Morning session 3B: **Diffusion Flames** ; Chair: **Rom McGuffin** , University of Colorado at Boulder

8:30	94-043	Studies of the Effects of Buoyancy on the Structure of Laminar, Opposed Flow Counterflow Diffusion Flames at Low Pressures, **J. J. Cor & M. C. Branch**, Center for Combustion Research, Department of Mechanical Engineering, University of Colorado, Boulder, CO.
8:55	94-044	Characteristics of Microgravity Gas Jet Diffusion Flames in the Laminar, Transitional, and Turbulent Regimes, **M. Y. Bahadori**, Science Applications International Corp., Torrance, CA, **L. Zhou**, University of California at Berkeley, Berkeley, CA & **U. G. Hegde**, Sverdrup Technology, Inc., Brook Park, OH.
9:20	94-045	Modeling NO_x Emissions in Turbulent Jet Flames: Effects of Buoyancy and Radiation, **A. E. Lutz & J. E. Broadwell**, Sandia National Laboratories, Livermore, CA.
9:45	94-046	CO and NO_x Emissions from a Laminar Coflow Diffusion Flame: A Comparison of Experimental and Theoretical Results, **J. C. Hewson & F. A. Williams**, Center for Energy & Combustion Research, University of California at San Diego, La Jolla, CA.
10:10		Break
10:40	94-047	Measurement of Mixture Fraction and Scalar Dissipation in Non-Premixed Reacting Flows Using Rayleigh Scattering, **J. A. Muss, R. W. Dibble, & L. Talbot** Department of Mechanical Engineering, University of California at Berkeley, Berkeley, CA.
11:05	94-048	A Bifurcated Diffusion Flame, **J. R. Hertzberg, M. Cuddy, J. Cloutier, R. Eckman, B. Gebre-Mariam, & T. Saffell**, Center for Combustion Research, Department of Mechanical Engineering, University of Colorado, Boulder, CO.
11:30	94-049	A Bifurcation Analysis of High-Temperature Ignition of $H_2 - O_2$ Diffusion Flames, **A. L. Sánchez**, Center for Energy & Combustion Research, University of California at San Diego, La Jolla, CA, **A. Liñán**, Universidad Politécnica de Madrid, Madrid, Spain & **F. A. Williams**, Center for Energy & Combustion Research, University of California at San Diego, La Jolla, CA.
11:55	94-050	Supersonic Hydrogen - Air Jet Flames: Flame Lengths Compared to Scaling Analysis, **H. Huh, Y. Yoon, J. M. Donbar, & J. F. Driscoll**, Department of Aerospace Engineering, The University of Michigan, Ann Arbor, MI.
12:20		Lunch