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Minutes of the

Workshop on Premixed Turbulent Combustion
Lawrence Berkeley Laboratory
Berkeley, California USA 94720

August 22-23, 1988

Edited by
R.K. Cheng and I.G. Shepherd

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INTRODUCTION

The workshop on premixed turbulent combustion was held at Lawrence Berkeley Laboratory, Berkeley, California on August 22 and 23, 1988 and was scheduled to follow the 22nd International Combustion Symposium in Seattle, Washington to attract domestic and international participants. The purpose of the workshop was to provide a forum for a focused group of theoretical and experimental researchers active in the field of premixed turbulent combustion research to discuss freely the current status and the future goals and directions of their programs. Since the emphasis of the meeting was on discussions without formal presentations, the optimum number of participants was set at 20.

Thirty invitations were sent together with questionnaires to solicit suggestions for discussion topics and for the agenda (Appendix 1). Eighteen responses were received, and the answers to the questionnaire were categorized, summarized (Appendix 3) and distributed to most of the participants prior to the workshop. Based on the answers to the questionnaire, four discussion topics were selected for the sessions (Appendix 4). They were (1) Regimes of premixed combustion (2) Comparison between experiments and models (3) From laboratory to real flames and (4) General open discussion.

Session 1

Regimes of Premixed Combustion

Co-chaired by R. K. Cheng and I. G. Shepherd

The session began with a discussion of the initial conditions of the available laboratory premixed turbulent flame data as shown on a parametric plane (Fig. 1 and Table 1). This representation, known in France as the Borghi-Barrere diagram (B-B), has appeared in various forms in many review articles of both laboratory flames and engine simulators. As shown in Fig. 1, the conditions of the laboratory flame experiments are limited to the wrinkled laminar flame regimes. The mixing control limit which has been associated, for example, with engine combustion is not yet covered. Most agreed that this means of representing the conditions is acceptable for showing the order of magnitude of the experimental conditions but that it does not give a complete representation because of several limitations. (1) It relies on Kologoroff scaling to relate the Damkohler number, Da, with the Reynolds number, Re, and Karlovitz number, Ka. Since the turbulence cascade is valid only for isotropic grid type turbulence, problems may arise when using this representation for I.C. engines and flames in shear layers and jets, for example. (2) There are different ways to determine the turbulence length scales and laminar flame thickness. Depending on the means of estimating the length scale and laminar flame thickness (thermal or reaction zone), the values of Da and Ka can vary by an order of magnitude therefore shifting the locations of the experimental conditions on this plane. Other limitations mentioned were the lack of any indication of the physical limits for stability and extinction. The use of a third dimension representing flame stretch, transient properties, and the variation of molecular properties within the flame was also proposed.

The proper means of representing the conditions in I. C. engines on this plane were subsequently discussed. Issues concerned with the selection of appropriate turbulence properties of the approach flow where complex transient phenomenon are involved were raised. For example, many papers reported rms fluctuations in the order of m/s with the associated length scales in the mm range. These magnitudes imply small Damkohler numbers which may even exceed the extinction limit of a corresponding laminar flame. Although many studies have indicated that the regimes of combustion in I.C. engines are significantly separated from those of laboratory flames, many questions remain unresolved. For example, how realistic are these fluctuations and length scales? Do the fluctuations in the mean velocity which cause the large rms have any real significance for the local propagation of the flamelet? Are the smaller scale fluctuations more significant for the local flame propagation rate? If the small scales are more significant, the regimes of the I.C. engines and laboratory flames would be much closer. The same questions also apply to premixed turbulent flames in shear flows where the flowfields are characterized by strained surfaces which do not behave according to homogeneous scaling hierarchies. In addition, the similarity of the behavior of the steady state flames to those of the configurations involving large shear were discussed.

There was a general consensus that the range of experimental conditions of laboratory flame should be extended to cover higher turbulence and distributed reaction zone regimes and that stability and extinction limits should also be explored. Various experimental methods for extending the conditions to these regimes were mentioned and briefly discussed. The challenges of how to distinguish between flames of different regimes were identified. It was agreed that by merely locating the initial conditions on a given parametric plane is insufficient. This is because boundaries marked by critical values of Da and Ka cannot be interpreted as hard boundaries and hence the magnitudes of the parameters do not a priori specify the regime of combustion. Also to help interpret the values of Da and Ka, they should be quoted together with supplemental information such as the method used to estimate the turbulence length scales (if not measured directly), the definition of laminar flame thickness and the expansion ratio of the mixtures. But all agreed that the regimes can only be established by supporting experimental evidence. This information is most significant when comparing experiments with theories. The lack of obvious experimental criteria for identifying the flame regime using single point type data was raised. One of the main obstacles currently faced by experimentalists is that very little is known about the detailed features of the flame zone in the various regimes. One suggestion was to use the bimodal pdfs of scalar fluctuations as the criterion to specify the laminar flamelets. As to the distributed reaction zone regime, the criterion seems to depend on what are considered to be thick flames. Since experimental determination of the instantaneous local flame thickness is extremely difficult, the key to the selection of this criterion may lie in the measurement of the local reaction rate. Another suggestion was to explore the time history (in the Lagrangian sense) of the flame development and whether or not the history affects the physics of local flame propagation.

Some recent studies of high turbulence premixed flames with conditions within the distributed reaction regime were presented by A. Yoshida. The configuration consists of interaction of two opposing jet within the confine of parallel plates. Details of the experiments and the implication of the results were discussed.

Session 2

Comparison between Experiments and Models

Co-chaired by F. C. Gouldin and P. A. Libby

The discussion began by re-examining the usefulness of the concept of turbulent burning speed, S_T. The main problem is that the concept only applies to 1-D flames or perhaps to 2-D 'normal flames', but there appears to be no consistent method to define it in experiments. F. C. Gouldin suggested that this concept has 'outlived its useful life' and proposed an alternate parameter called the turbulent burning velocity C_T which is based on estimating the mass flux rather than on a velocity. Further elaboration of this concept is included in Appendix 5. In this concept, the flame brush thickness l_T then becomes a significant parameter and subsequent discussion was centered on how to determine and predict this thickness. One of the proposed methods to predicted flame brush thickness was based on turbulent diffusion. The problems associated with the continuous growth of flame thickness indicated by this concept were raised and discussed. Other methods to predict flame brush thickness based on competition between Markstein instability and dampening effects of combustion and calculation of flame wrinkles with different strain rates were also discussed briefly.

Session 3

From Laboratory to Real Flames

Co-chaired by I. Gokalp and L. Talbot

The session started by addressing some general questions pertaining to the definition and characterization of real flames (i.e. flames found in practical systems). These questions were the following:

(1) What are real flames?
(2) Are the same parameters used to characterize laboratory flames relevant for real flames?
(3) What additional parameters should be considered in describing the turbulent flame structures in real systems?

(4) What are the ranges of the basic parameters, i.e. Re, Da, and Ka, that should be considered in real flames?
(5) What are the specific problems when the predictions of a model or theory are to be compared to the actual performance of a real system?

The participants agreed that the list of real premixed turbulent flames should include unwanted explosions, lifted diffusion flames where partial premixing may occur, and distributed sprays in addition to those in practical systems such as internal combustion engines, combustors, and furnaces. One of the unifying themes in the theoretical treatment of these systems is the inclusion of finite rate chemistry.

The challenges in modeling these system were discussed. Given the fact that the range of operating conditions may span more than one flame regime and non-uniformities exist within the various regions of the system, can the flame zone be characterized by a single turbulent premixed flame structure, or should all the flame structures indicated within the range of initial conditions be considered? In addition, the consideration of other effects such as pressure effects, cycle to cycle variations, heat transfer between the flame and the combustor wall, and transient effects should be included in the list of parameters.

With regard to the use of laboratory flame to assist in understanding the real flames, it was pointed out that exploring flames with low and high ranges of the Reynolds number and Da number would be very useful. For example, low Reynolds number flames would clarify the buoyancy and stability problems, whereas a high Reynolds number range woould be useful for studying extinction of stabilization problems. However, most agreed that it is not an easy task to vary independently the Reynolds and Damkohler numbers in laboratory experiments.

As to comparisons between measurements in real systems and theoretical predictions, different bases for such comparisons were discussed. A global parameter which could be determined by experiments would be useful but there does not seem to be an obvious candidate. The characteristics of flame structures in a real system were also proposed. Most agreed that before the choice can be made a review of what current models can predict and at what confidence level seems necessary. The predictive capabilities and limitations of some current models were discussed. It was pointed out that many aspects regarding the flowfield of real systems can be predicted with reasonable confidence. But concerning the modeling of flame structures and burning rates, the current approaches are quite crude. It was also stressed that models successful in predicting the turbulence field may not work for flames. For example, the density dependence of the exchange coefficient in k-type models is not known. The necessity of 3-D predictions in engines was also emphasized.

As an example of the research in real systems, R. F. Sawyer gave a brief synopsis of the current status of the experimental and theoretical work in I. C. engines. He pointed out that there are many interrelated problems of practical and fundamental interest. However, the area of success in modeling engine combustion is not in predicting the reaction rate but in predicting specific fluid motions and heat transfer within the cylinder. A list of important unsolved problems would include: how to obtain complete combustion; engine knock; pollutant formation; and combustion stability.

Session 4

General Open Discussion

Co-chaired by R. K. Cheng and J. F. Driscoll

This session began by soliciting from the participants their comments and impressions of the papers on turbulent combustion presented at the 22nd International Combustion Symposium. The materials presented in several papers on premixed and non-premixed turbulent flames were discussed in more detail. The overall impression was that the Symposium papers concentrated more on laboratory flames than on practical systems. Furthermore, there were more studies of the chemistry in non-premixed flames than in premixed flames.

The second half of the discussion was on the partially premixed flames and their theoretical treatments. Several current approaches were presented and discussed.

Table 1

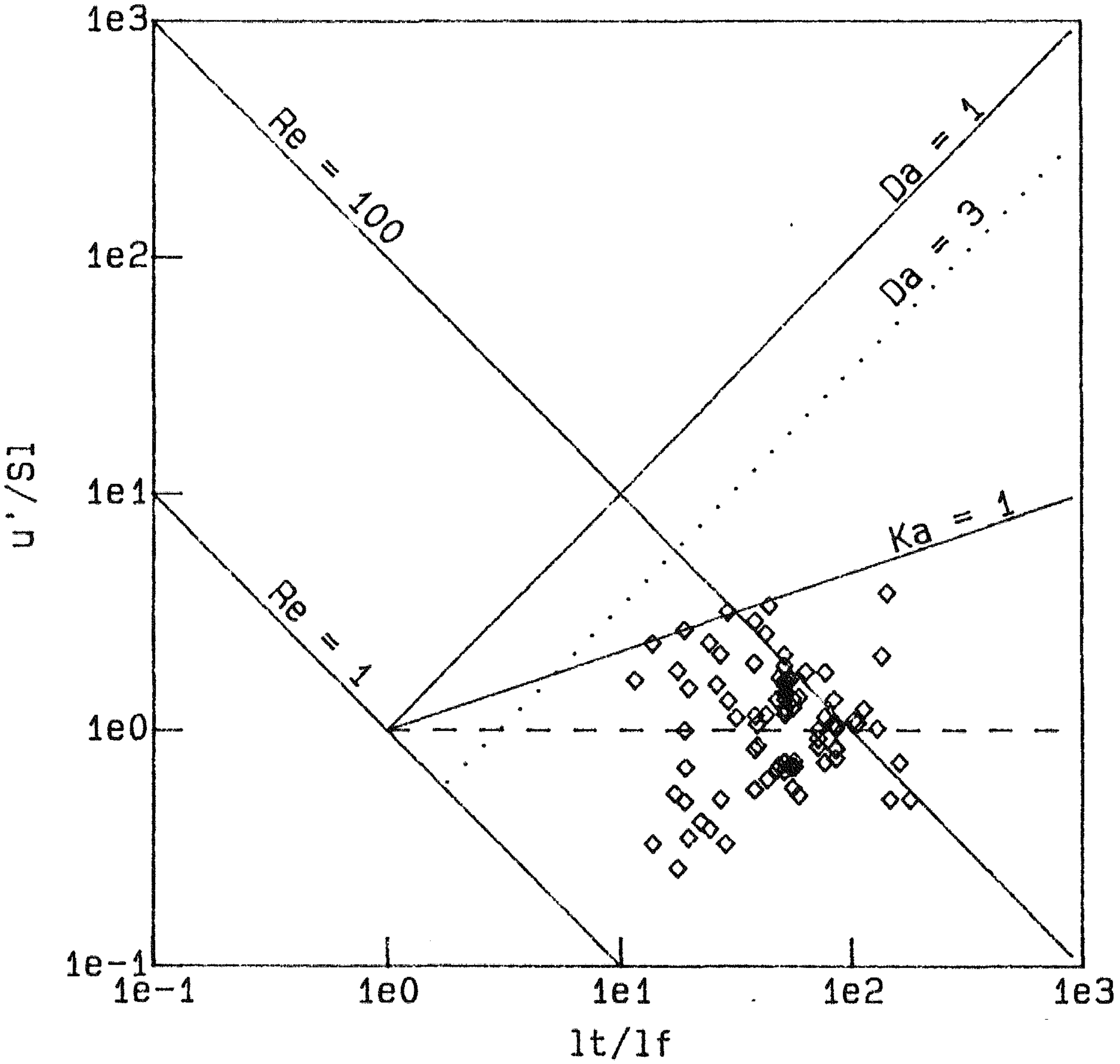

```
# Experimental conditions of premixed turbulent flames
# studies compiled by Beatrice Deschamps, Aug. 1988.
#
#
#
# Cheng and Ng C2H4 v-flames
#phi    Re      Da      l       u'      del l   Sl      u'/sl   l/del l
.75     116.7   220.94  .5      35      .0031   48      .73     161.3
.8      90      352.9   .45     30      .0025   59      .51     180
.7      75      288.35  .45     30      .0034   44      .51     147.06
.75     130.67  91.79   .4      49      .003148 48      1.02    129.02
.75     138.83  91.79   .35     59.5    .0031   48      1.23    112.9
#
#
# Cheng unpublished Bunsen flames CH4
0.88    38.4    71.08   .192    30      41      .0037   .73     51.89
1.15    27      69.8    .225    18      29      .0052   .62     43.27
1.15    34      45.6    .204    25      29      .0052   .86     39.23
1.15    282     65.9    .706    60      29      .0052   2.06    135.77
.714    148.8   13.15   .221    101     30      .0050   3.36    44.2
#
#
# Cheng et al 1988 (reaction rate paper);CH4 Bunsen Flames
.7      63.8    42.05   .3      31.9    .0058   26      1.23    51.72
.7      84      31.9    .3      42      .0058   26      1.62    51.72
.7      84.4    31.9    .3      42.2    .0058   26      1.62    51.72
.85     66      84.65   .3      33      .0038   39      .85     71.95
.85     72      78.2    .3      36      .0038   39      .92     71.95
.85     78      71.95   .3      39      .0038   39      1       71.95
1.0     65.2    112.77  .3      32.6    .0035   43      .76     85.71
1.0     70.8    104.52  .3      35.4    .0035   43      .082    85.71
1.0     87.4    84.03   .3      43.7    .0035   43      1.02    85.71
.7      70.2    38.3    .3      35.1    .0058   26      1.35    51.72
.7      80      33.58   .3      40      .0058   26      1.54    51.72
.7      108     24.87   .3      53      .0058   26      2.08    51.72
#
#
# Cheng et al 1988 (reaction rate paper) CH4 V-flames
1.0     71.2    103.26  .3      35.6    .0035   43      .83     85.71
1.0     72      102.04  .3      36      .0035   43      .84     85.71
.7      61      44.205  .3      30.5    .0058   26      1.17    51.72
.83     87      67.67   .3      43.5    .0039   38      1.14    76.92
.83     79      73.96   .3      39.5    .0039   38      .73     76.92
.83     36      70      .2      27.6    .0039   38      .73     51.28
.83     33.87   76.5    .2      25.4    .0039   38      .67     51.28
.7      97.4    27.7    0.3     4.87    .0058   26      1.87    51.72
.7      74.6    36.17   .3      37.3    .0058   26      1.43    51.72
```

Table 1

#phi	Re	Da	l	u′	del l	Sl	u′/sl	l/del l
#								
# Driscoll. Oblique CH4 flames.								
.7	7	31.53	.01	14	.0058	26	.54	17.24
.8	7	55.44	.01	14	.0044	34	.41	22.27
1	7	80.58	.01	14	.0035	43	.33	28.57
#								
#								
# Shepherd Moss Bray C3H8 Combined flames								
1.2	533	37.5	1	.8	.007	21	3.81	142.86
#								
#								
# Cho et al Stagnation CH4 flames								
1	38	81.6	.2	30	.0035	43	.70	57.14
.9	38	79.36	.2	30	.0036	42	.70	55.55
1	87	81.6	.3	45	.0035	43	1.05	85.7
.9	87	77.85	.3	45	.0036	42	1.07	83.3
#								
#								
# Boukhaita and Gokalp small CH4 Bunsen flame								
.8	41	76.78	.25	25	34	.0044	.74	56.82
.8	111	62.29	.37	46	34	.0044	1.35	84.09
.8	130	42.90	.34	60	34	.0044	1.76	77.27
.7	111	36	.37	46	26	.0058	1.77	63.79
1.0	111	98.78	.37	46	43	.0035	1.07	105.7
.9	111	93.4	.37	46	42	.0036	1.1	102.77
#								
#								
# Goix et al H2 flames								
.4	20	44	.19	.26	23	.06	1.13	31.67
.4	20	16	.115	.16	23	.06	.696	19.17
.4	40	38	.39	.17	16	.1	1.06	39
.4	40	17	.26	.25	16	.1	1.56	26
.43	20	7.5	.115	.26	16	.1	1.63	11.5
.43	20	20	.19	.16	16	.1	1	19
#								
#								
# Smith and Gouldin CH4 V-flames								
1	6.9	56.3	.069	15	.0035	43	.35	19.7
1	29.9	43.05	.069	65	.0035	43	1.51	19.7
.85	4.6	68.08	.069	10	.0038	39	.26	17.7
.85	32.2	9.89	.069	70	.0038	39	1.79	17.7
.75	4.6	41.8	.069	10	.005	30	.33	13.8
.75	32.2	9.89	.069	70	.005	30	2.33	13.8
1	13.9	53.14	.095	22	.0035	43	.51	27.1
1	57	12.97	.095	90	.0035	43	2.09	27.1
.85	9.5	63.95	.095	15	.0038	39	.38	24.3
.85	57	10.52	.095	90	.0038	39	2.34	24.3
.75	9.5	38	.095	15	.005	30	.5	19
.75	50	7.14	.095	80	.005	30	2.66	19
1	49.66	36.7	.149	50	.0035	43	1.16	42.57
1	109.26	16.6	.149	110	.0035	43	2.56	42.57
.85	44.7	33.2	.149	45	.0038	39	1.15	38.2
.85	109.26	13.2	.149	110	.0038	39	2.89	38.2
.75	39.73	21.95	.149	40	.005	30	1.33	29.2
.75	94.37	9.2	.149	95	.005	30	3.17	29.2

Table 1

#phi	Re	Da	l	u′	del l	Sl	u′/sl	l/del l
#								
# Gouldin and Dandaker CH4 air flames								
1	38	77.6	.19	30	.0035	43	.70	54.3
1	88.67	33.3	.19	70	.0035	43	1.63	54.3
.85	34.83	68.6	.19	27.5	.0038	38	.71	48.7
.85	82.33	29.34	.19	65	.0038	39	1.66	48.7
.75	31.66	45.6	.19	25	.005	30	.83	38
.75	72.83	19.79	.19	57.5	.005	30	1.92	38
#								
1	31.67	112	.19	25	.0032	47	.53	59.4
1	82.33	43	.19	65	.0032	47	1.38	59.4
.9	31.67	98	.19	25	.0034	44	.57	55.9
.9	76.00	41.1	.19	60	.0034	44	1.36	55.9
.8	63.33	69.85	.19	25	.0040	37	.68	47.5
.8	63.33	35.18	.19	50	.0040	37	1.35	47.5
.6	29.13	67.86	.19	23	.005	30	.56	38
.6	67.13	67.86	.19	53	.005	30	.56	38
.7	76.00	44.7	.19	25	.0034	44	1.25	55.9
.7	69.66	44.7	.19	55	.0034	44	1.25	55.9



1e3
1e2
1e1
1e0
1e-1
u'/Sl
1e-1
1e0
1e1
1e2
1e3
lt/lf
Re = 100
Re = 1
Da = 1
Da = 3
Ka = 1

Figure 1

- For all the flames, we used the kinematic viscosity, ν, of air at 300K and the consistent S_L values for each fuel.

- δ_L is determined by

$$\delta_L = \frac{\nu}{S_L}$$

- u′ and l correspond to the longitudinal component of the cold flow.

Key to Figure 1

lt = longitudinal turbulent time scale

lf = flame time scale

u' = longitudinal rms fluctuation

Sl = laminar flame speed

Re = Reynolds number based on longitudinal integral scale

Da = Damkohler number

Ka = Karlovitz number

Reference: N. Peters, 21st Symposium (International) on Combustion, (1986).

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Dear Colleagues,

This summer, many of you will be traveling to the West Coast to attend the 22nd International Combustion Symposium in Seattle. A group of us has decided to take this opportunity to meet at Berkeley after the Symposium to have a round table discussion on the future goals of our premixed turbulent flame research programs. We are planning to meet on the Monday and Tuesday (Aug. 22 and 23) following the Symposium, and would like to invite you to join us for this workshop.

Many of you may have already asked: why after the Symposium and not during? The reason is that the free time available to us during the Symposium is limited. Therefore, to have an unhurried meeting outside of the Symposium seems more appropriate to stimulate candid discussions and the free flow of ideas.

The following is a tentative list of topics for discussions. Please give us suggestions on additional topics by completing the enclosed questionnaire regardless of whether or not you are planning to attend.

(1) What can be done to increase communications and stimulate more collaborations between experimentalist and theoreticians?

(2) What problems (e.g. burning velocity, flame brush thickness, flame brush structures) for what conditions (e.g. wrinkled laminar flames, distributed reaction) may be considered solved?

(3) What experimental data do theoreticians need? What should be observed? Measured? Why?

(4) The scaling laws for regimes of premixed turbulent flames and their implications to experimental data interpretations. Is understanding the distributed reaction zone the key to the study of high Reynolds number and low Damkohler number flames?

Since the focus of the meeting is on discussions rather than presentations, the ideal number of participants should be less than twenty. We hope to attract most of you who have been active in premixed turbulent flame research to come. In addition to the technical agenda, some social events are also planned. So, please let one of us know at your earliest convenience if you are interested in participating and return the enclosed questionnaire to Robert Cheng. If you cannot come we would appreciate your answers and input to the discussion topics.

Robert Cheng (415) 486-5438 Telex: 910-366-2037

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Fred Gouldin (607) 255-5280

Iskender Gokalp (38) 63-06-17 (in France)

Please return the questionnaire to

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U.S.A.

Name ________________________________

Address ________________________________

____

____

Tel: ________________________________

I will/will not be able to come to Berkeley to participate in the Workshop on Premixed Turbulent Combustion.

I would like to suggest the following topics for discussion during this meeting.

In my opinion the following premixed turbulent combustion problems are considered solved:

and the following problems are partially solved or can be solved by existing models and diagnostics:

I believe that the following problems are most important and need to be addressed in the near future:

For theoreticians: Which aspect of your model needs further development? What experiments would be helpful? What should be measured, observed and why?

For experimentalists: Which aspects of your measurements are least understood? What kind of experiments can you perform (within the context of your current funding or if more funding is available) to help test the current theories e.g. Pope's, BML, Clavin-Williams, vortex dynamics etc.?

In what way does fundamental premixed turbulent combustion contribute to combustion technology?

Additional Comments:

WORKSHOP ON PREMIXED TURBULENT COMBUSTION
Lawrence Berkeley Laboratory
Berkeley, CA 94720

Aug 22 - 23, 1988

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WORKSHOP ON PREMIXED TURBULENT COMBUSTION

AUGUST 22 AND 23, 1988

LAWRENCE BERKELEY LABORATORY
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QUESTIONNAIRE SUMMARY

Key to categories of comments.

(1) General
(2) Flames with Da >> 1
(3) Flames with moderate or small Da
(4) Burning speed (S_T)
(5) Comparison between models and experiments
(6) Physical limits and limitations of models and experiments
(7) Transitions between low to high Da, Re, M (Mach number)

1. I WOULD LIKE TO SUGGEST THE FOLLOWING TOPICS FOR DISCUSSION DURING THIS MEETING:.

(1) - Phenomenological aspects, in particular the fluid mechanical structure and mechanism.
- Structure of turbulent premixed turbulent flames.
- Factors controlling characteristic scales.
- Turbulence generation, especially that due to pressure fluctuations.

(2) - Behavior of local flame front.
- Relationship between flame wrinkle sizes and eddy sizes in the approach flow.
- Mechanism of flame wrinkling in turbulent premixed flames, laminar flame instability.

(3) - Distributed reactions, islands of unburned gas: postulated but what Da, Re needed to actually observe them?
- Turbulence (flow)-combustion interactions in premixed flames at intermediate Damkohler numbers.
- Finite chemistry effects.
- Structure of the distributed reaction zone.
- Distributed flamelet concept.

(4) - Importance of mechanisms that affect burning velocity of a curved laminar flamelet: stretch, thrust from gas expansion, Lewis number effects, heat flux focusing.
- What turbulent burning velocity data should we agree upon is most accurate for verifying models? Bradley's double kernal, Ballal's?
- Is the wrinkling of the flame front the only one major mechanism for an increase of the burning velocity in weak turbulence regions? What are other possible mechanisms?

- Is the use of the turbulent burning velocity convenient for the description of combustion at high turbulence intensities? What about the use of combustion density?
- Why show the measurements in rich and poor flames different dependencies on turbulent parameter?
- How useful is S_T?
- What is the real significance of measuring and correlating of the turbulence burning speed and their applications, given the fact that the data are probably dependent on flame geometry.

(5) - What correlation measurements (i.e. scalar 2-point) are most useful?
- What quantities other than S_T should models predict?

(6) - Lagrangian vortex models or stochastic models-limitations, future use of each.
- Turbulent premixed flames at intermediate and high Mach numbers.
- How to reconcile the M viewpoint with the recent theories (Yakhot's, Sivashinsky's) which give $S_T=f(u_L,u'_{rms})$ and assume the existence of a "leading front".
- What happens close to c bar = 0?
- Quenching.

(7) - The mechanisms of the transition from one region of turbulence premixed combustion to another regime.
- In a given regime, how does the flame structure change when you modify systematically one of the important flow or combustion parameters?
- Mapping combustion regimes and transitions between them.

2. IN MY OPINION THE FOLLOWING PREMIXED TURBULENT COMBUSTION PROBLEMS ARE CONSIDER SOLVED:

(1) - Stochastic properties.
- Statistical interpretation of experimental records.
- The answer is too configuration dependent, but some global features of the flame structure may be configured and understood.

(2) - Flames at high (very high) Damkohler numbers (flame sheets, flamelets).
- The effects of mild strain and curvature on laminar pre-mixed flames.
- The use of conditional averages for describing the structure of large Damkohler number flames.
- Applicability of the BML thermo-chemistry model over a wide range of conditions.
- Parameter domain for flame sheet model of wrinkled laminar flame.

(4) - S_T increases with increasing u' for weak turbulence.

(6) - High turbulence intensity (u'/S_k) can cause flame extinction.
- The role of the laminar flame instability in the flame wrinkling in turbulent premixed flames.

3. AND THE FOLLOWING PROBLEMS ARE PARTIALLY SOLVED OR CAN BE SOLVED BY EXISTING MODELS AND DIAGNOSTICS:

(1) - The effect of the unburned gas turbulence on the flame wrinkling in turbulent premixed flames.

(2) - Burning rates and stability at high equivalence and Damkohler number, and large scale turbulence.
- Effects of mean pressure gradient on turbulent transport.
- Mechanisms of flame front turbulence growth.
- The role of mean pressure gradients and flame geometries on flame structures.
- Correlation between flame area and reaction rate for large Damkohler number flames.
- The estimation of the turbulent burning velocity for the wrinkled laminar flame.
- Stability of laminar flame sheets.

(5) - Mean and r.m.s. profiles can be "predicted" with a little fine tuning.
- Time and space statistics of the flame front movements.

(6) - The stretch of a flame front seems to be one major reason for flame extinction.

4. I BELIEVE THAT THE FOLLOWING PROBLEMS ARE MOST IMPORTANT AND NEED TO BE ADDRESSED IN THE NEAR FUTURE:

(1) - Flame structure.
- Partially premixed/stratified flames.
- Phenomenological aspects, in particular the fluid mechanical structure and mechanism.
- Flame-generated turbulence at high rates of heat release.
- Combustion phenomena at the flame front during premixed turbulent combustion.
- Turbulence-chemistry interactions in turbulent premixed flames.
- 2D and 3D numerical solution methods (steady-state and time-dependent.
- Role of pressure fluctuations on turbulence generation.
- Elucidation of the dependence of flame properties on burner configuration.
- Determination of the flow and wall transfer in a turbulent flow with piston compression and combustion.

(3) - Is conditional averaging model applicable to moderate Damkohler number flames?
- Finite chemistry effects.

- Characterizing distributed reaction zones.
- The structure of the distributed reaction zone.
- The prediction of the turbulent burning velocity for the distributed zone.
- Existence (or non-existence) of distributed flamelet domain for premixed turbulent flames.

(4)
- Better burning velocity data.
- Mean reaction rate.
- The mechanism of the increase of the burning velocity due to the turbulence effect.
- The significance of turbulence stretch on local flame propagation rate.
- Significance of S_T
- Turbulent flame speed.

(5)
- Characteristic length and time scales.
- Distribution of strain rates.
- Scalar & velocity time & length scales in the flame zone.
- How does the flame modify the turbulence?

(6)
- High Reynolds numbers.
- Extinction of turbulent flames.
- Flame stability (stabilization).
- What is the exact condition for local extinction in a turbulent flame? What is the mechanism?
- Role of laminar flamelet intrinsic dynamics (e.g. Landau-Dorrieus effect, influences of curvature and stretch?) in turbulent flame propagation?
- Local flame quenching by turbulence stretch.

(7)
- Effect of small and intermediate scales of turbulence on flame structure and speed.
- Transition from flamelet to distributed combustion - when does it happen (without extinction) and what does it look like?
- In a given regime, how does the flame structure change when you modify systematically one of the important flow or combustion parameters?

5. FOR THEORETICIANS: (a)WHICH ASPECT OF YOUR MODEL NEEDS FURTHER DEVELOPMENT? (b)WHAT EXPERIMENTS WOULD BE HELPFUL? (c)WHAT SHOULD BE MEASURED, OBSERVED AND WHY?

(a)
- Systemization of the treatment of flow fields, involving combined effects of the transfer of species, momentum, and heat, associated with the evolution of exothermic energy.
- Model-problems associated with realizability.
- Higher-order closure with special regard to the chemical source term closure.
- Ability to predict radical concentrations and minor species in turbulent premixed flames.
- Are Kolmogorov's scaling laws valid just ahead of the flamelets, especially the "leading one". If no, how to measure the spectra

there, and their relationship with those of the incoming, far upstream, flow?
- Configuration dependency of the results.

(b) - Yielding results of relevance to phenomenological aspects.
- The measurements currently being performed, especially those using conditioning, are great. The configurations need more attention. For a given geometry it is extremely valuable to have as widely different thermal chemistry as possible.
- Conditional velocity measurement to study turbulence generation.

(c) - Image recording and processing.
- Careful examination of flame structures by simultaneous multi-point measurement of aerothermo-dynamic variables.
- 2-D imaging and passage time measurement.

6. FOR EXPERIMENTALISTS: (a)WHAT ASPECTS OF YOUR MEASUREMENTS ARE LEAST UNDERSTOOD? (b)WHAT KIND OF EXPERIMENTS CAN YOU PERFORM (WITHIN THE CONTEXT OF YOUR CURRENT FUNDING OR IF MORE FUNDING IS AVAILABLE) TO HELP TEST THE CURRENT THEORIES E.G. POPE'S, BML, CALVIN-WILLIAMS, VORTEX DYNAMICS,ETC.?

(a) - The changes in the scalar and turbulence scales with mixture and flow conditions.
- Distributed flamelet domain

(b) - At present we are trying to measure turbulent burning velocities S_T at high u'/S_L ratios, both in stationary and instationary flames (stagnation flame system and explosion bomb method).
- The measurement of the rate of heat transfer from a turbulent premixed flame to a solid wall. The investigation to explore effective ways to enhance the rate of heat transfer by controlling the flame front turbulence.
- Parametric investigations of the flame scalar and dynamic structures.
- The flow visualization and the image processing technique will be helpful for the analysis by the fractal geometry.
- The turbulence characteristics in the reaction zone has been least understood. The power spectra of turbulence will provide a powerful tool for the study of the turbulence-laminar flame interaction.

7. IN WHAT WAY DOES FUNDAMENTAL PREMIXED TURBULENT COMBUSTION CONTRIBUTE TO COMBUSTION TECHNOLOGY?

- It is depressing that after many years of research, measurements of turbulent burning velocities are not correlated using correlations that everyone agrees upon and that models cannot predict turbulent flame speeds. Non-premixed combustion, which is used in more practical devices, can benefit from premixed flame technology in the study of

lifted non-premixed flames, staged combustion, reburning of NO_x in products, group combustion of sprays.
- By exerting a significant impact upon the progress of propulsion technology.
- Understanding and quantification of events in: fast-combustion engines, lean-combustion engines, controlled-combustion engine.(AFG)
- Develop/test models for practical systems, e.g. SI engines.
- Emphasize certain factors, e.g. density fluctuations.
- Spark-ignition engines.
- Other systems in which premixing (even partial premixing) can occur.
- Flame stabilization.
- Prediction of burning velocity for a given turbulent flow.
- It will be useful to reach new concepts of turbulent combustion in combustors and to understand flame propagation during accidental gas explosion.
- It brings to light the positive (increase power) and negative (local extinction, pollutant formation) aspects of turbulence on combustion.
- By showing the trends in the modification of some global characteristics when the operating conditions are changed.
- The rationalization of the design of the IC-Engine.
- More predictive capability for internal engine combustion.

ADDITIONAL COMMENTS:

(1) - Other mean properties such as the proper turbulent flame brush thickness as prescribed by Lagrangian flowlines can help to close the dc/dx terms.

(5) - It would be useful for session organizers to allow some sessions to concentrate on the fine details of models or experiments, but keep one session general for communication between modelers and experimentalists. My own preference is to minimize discussion on how the pdf, vortex or fractal models do their bookkeeping and how they predict mean profiles and instead talk about the physical mechanisms that models need to model reaction rate, such as flame oscillation frequency, flame area and structure.
- Value of full turbulence simulations, e.g. with thin flames, when these can be calculated with confidence.
- Test of empirical model closures.
- We need reasonable interpretation of the observed phenomena of premixed turbulent combustion, and appropriate theories to help the interpretation of the experimental results are most desirable.
- Experiments involving measurements of chemical species present in the reaction zone may help to infer the variation of the local reaction rate due to flame stretch.

(7) - The proper way to interpret the "intermediate" state measured by techniques such as Rayleigh scattering.
- We need to discuss in detail some specific problems and their relevance, such as the influence of u'/S_L, the question of the "flame generated turbulence", influence of the Damkohler number, etc.

- Measurements of high Re are mandatory.
- It would be good if some basic experiments and calculations were suggested-as well as condition needs listed. Some of the turbulent modeling I have seen has been quite limited.

WORKSHOP ON PREMIXED TURBULENT COMBUSTION
AUGUST 22 AND 23, 1988

LAWRENCE BERKELEY LABORATORY
BERKELEY, CA 94720

All sessions will be held in LBL Bldg. 70A Conference Room

9:00 - 9:15am	Opening and Welcome (R.K. Cheng & N. J. Brown)
<u>Session 1</u> Mon., Aug. 22 9:15 - 11:30am	Regimes of premixed combustion. -Qualitative vs. quantitative description of the boundaries -What are the realistic physical boundaries, i.e., limitations, stretch, extinction, stabilization Moderators: R.K. Cheng & I.G. Shepherd
<u>Session 2</u> Mon., Aug.22 12:30 - 3:00pm	Comparision between experiments and models. -The significance of turbulence burning speed -How to compare 1 & 2-D models with 2 & 3-D flames Moderators: F. C. Gouldin & P.A. Libby
Mon. Aug. 22 7:00pm	Dinner, Mandarin House Restaurant 2025 Shattuck Ave., Berkeley
<u>Session 3</u> Tues., Aug. 23 9:00 - 11:30am	From laboratory to real flames. -Pressure effects -High Reynolds number Moderators: I. Gokalp & L. Talbot
<u>Session 4</u> Tues., Aug. 23 12:30 - 3:00pm	General open discussions -Current status of turbulent combustion research as conveyed by the Symposium papers -Partially premixed and non-premixed flames Moderators: R.K. Cheng and J.F. Driscoll

ON THE TURBULENT BURNING VELOCITY CONCEPT AND OTHER COMMENTS

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The turbulent burning velocity, u_t, defined by analogy to the laminar burning velocity is an ill defined and misleading concept that has far outlived its useful life, if in deed it ever had a useful life. A new definition and a new name for a global combustion parameter are suggested. Other comments regarding premixed turbulent flames are made.

Of primary importance to anyone studying combustion and in particular premixed turbulent flames is the existence of a combustion parameter which 1) characterizes the overall combustion rate and 2) is easily measured, e.g., the laminar burning velocity or the mass loading rate of a perfectly stirred reactor. The desire to find such a parameter certainly helps to explain why the concept of the turbulent burning velocity has persisted for so long.

For steady, unstrained laminar flames the burning velocity is a reasonably well defined physico-chemical property of the reactant mixture, and numerical calculations of it are in reasonable agreement with experimental data obtained in different types of flames, e.g., bunsen flames, and free flames (freely propagating flames). Such is not the case for turbulent flames for a number of reasons. u_t is not a physico-chemical property of the mixture; it depends on flow boundary conditions as well as the reactant mixture properties. In the presence of turbulence the governing conservation equations are so complex that it has been impossible to make a general investigation of the existence of a burning velocity. Williams (1970) discussed the burning velocity for a normal turbulent flame and defined it, effectively, as the mean flow velocity in the reactant stream before it enters the flame brush. Unfortunately it has not been possible to establish a normal flame in the laboratory except for very low turbulence levels which are of no practical interest. In addition there are theoretical results which suggest that a stationary normal flame is not possible; the flame brush thickness increases in time without bound.

Many different flame configurations have been studied experimentally, e.g., bunsen flames, v-flames, wake flames, free flames and stagnation flames. Several different methods for measuring u_t have been suggested. In the author's opinion, available u_t data are inconsistent and do not support the hypothesis that there is, in some general sense, a turbulent burning velocity which can be defined by analogy with the laminar burning velocity and which is a universal function of the flow and reactant mixture properties. I do not mean to say that a burning velocity cannot be defined for a particular flame - I believe that one can be - but rather that there is no reason to expect that the definition has significance beyond a particular flame configuration or experiment and that one should expect that the relationship between burning velocity on the one hand and flow and mixture properties on the other is not universal.

While there is no universal burning velocity per se, it is possible to define in a straight forward manner a quantity which measures overall combustion rate and, therefore, is an important parameter for one to measure and calculate. This quantity has the units of velocity and will be called the turbulent combustion velocity, c_t.

Consider a streamtube defined by a certain mean mass flux, $\langle m_t \rangle$, and a volume, V_t, defined by the intersection with this streamtube of two surfaces defined by $\langle c \rangle = 0$ and 1. Let ρ_o be the reactant density and l_t the minimum distance between the two surfaces -- $\langle c \rangle = 0$ and 1*. (This definition of l_t implies that the streamtube lateral dimension is small and constant $\langle c \rangle$ surfaces may be assumed to be planar across the streamtube.) Then

$$c_t = \langle m_t \rangle / \rho_o A_t,$$

where

$$A_t = V_t / l_t.$$

Clearly this quantity is a measure of the overall combustion rate. For a normal flame it is equal to the the burning velocity defined by Williams. It's definition is unambiguous, but it may be very difficult to determine experimentally, since the boundaries of a streamtube must be determined.

Our hosts have just reported at the Symposium a method for measuring velocities along streamlines. This approach might be extended to the determination of V_t. I am confident that while measurements of c_t may be difficult, they can be performed. What is important is that the definition of c_t is physically significant and unambiguous. Without question it is

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* There may be cases where it is difficult to find $\langle c \rangle = 0$ or 1 surfaces. To define c_t it is necessary to define in some way surfaces which bound the time mean reaction zone. If such surfaces can not be determined, then the concept of a global combustion rate is not applicable since in such cases combustion in a streamtube is not confined to a finite volume.

better to focus our efforts upon the modeling and measuring of clearly defined quantities rather than to pursue ill defined though "measurable" quantities.

As noted above it has so far not been possible to establish a normal flame in flows with high turbulence levels. In general high turbulence Reynolds numbers are associated with high mean velocities since relative turbulence intensities vary from less than 10%, for grid turbulence, to about 20% for shear layer turbulence and high absolute turbulence levels are obtained only increasing the mean velocity. With high mean velocities oblique flames are the rule. Furthermore there are usually mean velocity gradients and streamline curvature present due to the flow configuration and heat release. As a consequence <c> constant surface are not expected to be parallel and these surfaces are curved. For modeling purposes, simple flame brush geometries, e.g., planar <c> constant surfaces, parallel <c> surfaces, are frequently assumed, and therefore, comparisons of model predictions with experimental data are ambiguous at best if not impossible. I would urge modelers to work on models which are applicable to mean flows which have variations in 2 and 3 dimensions.

Finally I would like to note the importance of pressure fluctuations. In the flamelet regime the density change occurs across the flamelets, and there must be a corresponding pressure drop which contributes to the pressure fluctuation field. If density inducted flow acceleration is significant, then pressure fluctuations across flamelets must be important. One should not lose sight of the potential importance of these effects when comparing model with experiment and model with model.