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14. ABSTRACT Turbulence generation and liquid breakup were studied due to their relevance to the dense combusting sprays found in propulsion systems. Measurements showed that flows resulting from turbulence generation consisted of drop wake disturbances embedded in a turbulent interwake region and also showed that both regions were unusual: the drop wakes were laminar-like turbulent wakes typical of intermediate Reynolds number wakes in turbulent environments, whereas the turbulent inter-wake region consisted of isotropic turbulence in the little studied final decay period. The properties of both regions were obtained from measurements of monodisperse particle (drop) flows and yielded ways to estimate their properties. New measurements showed the potential effectiveness of modifications of these methods to treat polydisperse particle (drop) flows of greater practical interest. Liquid breakup is important because it is the rate controlling process of dense sprays. Measurements successfully resolved the temporal properties of secondary drop breakup for large liquid/gas density ratios. Numerical simulations provided similar information about the related problem of liquid column breakup with the added advantage of treating small liquid/gas density ratios where measurements were problematical. Corresponding calculations of secondary drop breakup showed interesting similarities between liquid drop and column breakup as well as new ways to treat effects of density and viscosity variations on breakup.					
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Drop/Gas Interactions of Dense Sprays

Objectives:

Primary liquid breakup and turbulence generation by dispersed phases (particles or drops) are being studied due to their relevance to spray combustion processes of air breathing propulsion systems and liquid rocket engines of interest to the Air Force. The specific objectives of the two phases of the study are as follows:

- (i) **Liquid Breakup.** Complete measurements of primary breakup properties for the following conditions: (1) round nonturbulent liquid jets in gaseous crossflows because this is a classical spray atomization configuration of interest for afterburners and missile propulsion systems, (2) round turbulent liquid jets in gaseous crossflows because most practical injectors introduce some degree of turbulent disturbance to liquid flows in injector passages, and (3) aerated-liquid jets in gaseous crossflows because this configuration has attractive atomization and penetration properties for missile propulsion systems. In all cases, the following information is sought: definition of breakup regimes, liquid jet trajectories, conditions for the onset of breakup, conditions for jet breakup as a whole, drop size and velocity distributions after breakup as a function of distance along the jet and rates of liquid breakup as a function of distance along the jet.
- (ii) **Turbulence Generation.** Complete conditional measurements of interwake turbulence properties needed for a rational description of turbulence generation properties, and complete conditional measurements of the mean and fluctuating properties of particle wakes in turbulent environments representative of turbulence generation processes, considering polydisperse particle flows as dispersed phases. Complete theoretical interpretation of the measurements using classical methods of describing isotropic turbulence for the properties of interwake turbulence fields and similarity theory for the properties of particle wakes.

Status of Effort:

Progress toward achieving the research objectives of the liquid breakup and turbulence generation phases of the investigation is discussed, in turn, in the following:

Liquid Breakup. There were three main contributions to improved understanding of liquid breakup processes in dense sprays during the report period, as follows: (1) measurements, numerical computations and phenomenological analysis of the primary breakup properties of round nonturbulent liquid jets in gaseous crossflows were completed. (2) Measurements and phenomenological analysis of the primary breakup properties of round turbulent liquid jets in gaseous crossflows were initiated. (3) Finally, measurements and phenomenological analysis of the primary breakup properties of round aerated-liquid jets in gaseous crossflows were initiated. In all three cases measurements of drop size and velocity distributions after breakup and rates of liquid breakup are sought with the results interpreted and correlated using phenomenological analysis.

Turbulence Generation. There were two main contributions to improved understanding of turbulence generation during this report period, as follows: (1) new measurements allowed the properties of the interwake region of turbulence generation processes to be extended from earlier findings for monodisperse particle flows to more practical polydisperse particle flows, and (2) new measurements allowed the properties of the particle wake region of turbulence generation processes to be extended from earlier findings for monodisperse particle flows to more practical polydisperse particle flows.

Accomplishments/New Findings:

Research highlights for the liquid breakup and turbulence generation phases of the present investigation are discussed, in turn, in the following:

Liquid Breakup. Past experimental studies have established the temporal properties of secondary drop breakup for drops exposed to shock-wave disturbances (a step change in the ambient gas velocity around a drop to simulate breakup processes after drops appear in a continuous gas flow as a result of primary breakup), see Aalburg et al. (2003), Chou and Faeth (1998), Chou et al. (1997), Dai and Faeth (2001), Faeth (1996), and Hsiang and Faeth (1992,1993,1995), and have initiated studies of the breakup of round nonturbulent liquid jets in crossflow, see Mazallon et al. (1999). All of these studies were limited to large liquid/gas density ratios. Current work has considered three primary liquid breakup processes, as follows: (1) primary breakup of round nonturbulent liquid jets in uniform gaseous crossflows, (2) primary breakup of round turbulent liquid jets in uniform gaseous crossflows, and (3) primary breakup of aerated-liquid jets in uniform gaseous supersonic crossflows. The latter two of these flows were also limited to large liquid/gas density ratios.

Primary Breakup of Round Nonturbulent Liquid Jets in Gaseous Crossflows. A computational and experimental study of the deformation and breakup properties of nonturbulent round liquid jets in uniform gaseous crossflows was undertaken seeking to develop numerical predictions of these properties at conditions that are difficult to address using experiments. The time-dependent incompressible two-dimensional Navier-Stokes equations were solved in the gas and liquid phases in conjunction with the level-set method to determine the position of the liquid/gas interface of the deforming liquid jets. The computations were evaluated satisfactorily based on earlier measurements of flows over solid circular cylinders as well as present measurements of the properties of nonturbulent round liquid jets in crossflow (liquid jet cross stream deformation, liquid jet streamwise deformation and deflection, and breakup regime transitions). The main findings of the study were as follows: (1) remarkable similarities were observed between the deformation and breakup properties of nonturbulent round liquid jets in uniform crossflows and the secondary breakup properties of round liquid drops subjected to shock wave disturbances, (2) liquid/gas density ratio had a surprisingly small effect on the deformation and breakup of nonturbulent liquid jets subjected to uniform crossflows for liquid/gas density ratios greater than thirty (30) and when effects of liquid viscosity are small (Ohnesorge numbers less than 0.1), (3) the crossflow Reynolds number had little effect on liquid breakup properties for values larger than 50, however, as the small Reynolds number, Stokes flow regime is approached, liquid jet resistance to deformation and breakup increases significantly due to increased liquid column drag coefficients, and (4) a liquid column

deformation and breakup regime map, plotted as a function of the ratio of column-drag-force/column-viscous force ratio ($We^{1/2}/Oh$ where We is the crossflow Weber number and Oh is the crossflow Ohnesorge number) and the surface-tension-force/liquid-viscous-force ratio ($1/Oh$) yielded deformation and breakup regime boundaries at large Oh that were relatively independent of the other parameters of the flow and also quantified the relatively small effect of liquid/gas density ratio on flow regime transitions at these conditions. See Aalburg et al. (2003,2004) for a complete discussion of these results.

Primary Breakup of Turbulent Liquid Jets in Uniform Crossflow. An experimental study of the deformation and breakup properties of round turbulent liquid jets in uniform gaseous crossflows was undertaken seeking to develop information about this process in order to evaluate effects of turbulent disturbances within the liquid jet, frequently introduced by practical liquid injector passages, on jet breakup properties. Extensive work on this primary breakup process has been carried out earlier in this laboratory. This work was limited, however, to the primary breakup of round turbulent liquid jets in still gases with fully-developed turbulent pipe flow at the injector exit, see Sallam and Faeth (2003), Sallam et al. (2002), Wu and Faeth (1993,1995) and Wu et al. (1992,1995). Present measurements were carried out considering round liquid jets for various liquids produced using long injector passage lengths (greater than 50 injector diameters) with sufficiently-large injector Reynolds numbers to ensure fully-developed turbulent pipe flow at the injector exit, based on criteria developed by Wu et al. (1995). Crossflows were developed using the subsonic flow (relative to the jet) behind propagating shock waves in a shock tube and subsonic flows in a subsonic wind tunnel (the former to observe breakup properties along the liquid surface and the latter to observe breakup of the liquid jet as a whole). Observations of the primary breakup process were made using pulsed shadowgraphy and holography. Measurements planned for this study include: liquid jet cross stream deformation, liquid jet streamwise deformation and deflection, breakup regime transitions, onset of shear breakup along the liquid surface, the variation of ligament sizes, drop sizes and velocities after breakup as a function of distance along the liquid surface, and rates of liquid breakup as a function of distance along the liquid surface.

This work is still in progress but results thus far point to the importance of liquid turbulence properties on liquid breakup processes. In particular, light gases are far less effective for creating vorticity in the liquid than injector passage walls and liquid breakup simply cannot occur in the absence of liquid phase vorticity. Thus, many of the results in this case involve properties similar to those observed for primary round turbulent liquid jets in still gases, and are only mildly perturbed by effects of the crossflow.

Primary Breakup of Round Aerated-Liquid Jets in Supersonic Gaseous Crossflow. An experimental investigation of the primary breakup properties of round aerated-liquid jets in the annular flow regime exposed to a supersonic crossflow was undertaken. Single- and double-pulse shadowgraphy and holography were used to study the properties of the conical liquid sheet that extends from the jet exit for finite degrees of aeration (gas/liquid mass flow rate ratios greater than 2%) as well as the outcomes of primary breakup in the dense-spray region near the liquid jet itself. The results showed that the gas jet along the axis of the annular flow leaving the injector passage is underexpanded so that the excess pressure of the flow in this region forces the annular liquid sheet into a conical shape that extends from the injector exit. Primary breakup

occurred in a similar manner along both the upstream and downstream sides of the liquid jet (relative to the crossflow) which suggests that aerodynamic effects due to the crossflow are relatively weak near the jet exit. Surface velocities of the liquid sheet were measured and were used to develop correlations for the liquid sheet thickness and for the penetration of the sheet prior to its breakup as a whole. Sizes of ligaments and drops were measured along the liquid surface and were found to have constant diameters of 0.029 and 0.043 mm, respectively, independent of position along the liquid sheet and wide ranges of aeration levels, liquid/gas momentum flux ratios, injector exit passage diameters, liquid/gas momentum flux ratios, injector exit passage diameters and liquid properties for the ranges of these variables considered during the present investigation. Finally, drop size distributions satisfied Simmons' universal root-normal drop size distribution function with the ratio of the mass median drop size, MMD, to the Sauter mean drop size, SMD, or $MMD/SMD = 1.07$, which implies more nearly monodisperse drop size properties after aerated-liquid breakup than is encountered for other primary and secondary breakup properties.

Findings thus far have made significant progress toward understanding the breakup properties of aerated-liquid jets. An important finding is that crossflows, even supersonic crossflows, appear to have little effect on breakup because the process is dominated by the external expansion process of the gas flow at the axis of the annular flow near the injector exit. Given this finding, subsequent study of this flow can be carried out without needing time in a supersonic or subsonic wind tunnel, which is invariably limited. This study needs to complete measurements similar to those available for primary round nonturbulent liquid jets in uniform crossflows, e.g., ligament and drop sizes (after breakup) as a function of distance along the liquid surface, drop velocities after breakup as a function of distance along the liquid surface, rates of liquid breakup as a function of distance along the liquid surface, and conditions for breakup of the liquid sheet as a whole.

Turbulence Generation. Early studies showed that turbulence generation by particles (drops) involved particle wakes embedded in a turbulent interwake region (Parthesarathy and Faeth 1990a,b; Mizukami et al. 1992). Wu and Faeth (1993,1994,1995) subsequently showed that the wakes behaved like laminar wakes but with fast mixing due to the presence of turbulence (commonly referred to as "laminar-like turbulent wakes"). Subsequently, Chen et al. (2000) and Chen and Faeth (2000,2001), considering turbulence generation for monodisperse particle flows, showed that the turbulent interwake region consisted of isotropic turbulence in the rarely observed final-decay period defined by Batchelor and Townsend (1948). The current work of Lee et al. (2003) extends these observations to the turbulent interwake region of more practical polydisperse particle flows, using wake-discriminating laser velocimetry.

Chen and Faeth (2001) developed an analogy between grid-generated isotropic turbulence and particle-generated isotropic turbulence, when both were in the final-decay period. This yielded a very useful correlation between relative turbulence intensities in the streamwise and cross-stream directions, $(\bar{u}' \text{ and } \bar{v}')/U_p$, where U_p is the mean streamwise velocity of the particles relative to the gas, and the dimensionless rate of dissipation of mechanical energy of the particles, D . During the present investigation, mixing rules were developed to extend these ideas to polydisperse particle flows based on dissipation weighting of the effect of each particle size group. The resulting correlation of the measurements exhibits a universal correlation for both

monodisperse and polydisperse sized particles according to the square root of D , as suggested by the theory.

Other experiments completed during this report period involved wake-discriminating measurements of energy spectra and characteristic length scales for the turbulent interwake region of polydisperse particle flows. A remarkable feature of these results was the large range of length scales observed (up to 1000:1) even though turbulence Reynolds numbers were small (less than 4). Present results yielded the ratios of the streamwise integral length scale, L_u , to the Taylor dissipation scale, λ , as a function of the turbulence Reynolds number, Re_λ . Surprisingly, L_u/λ decreases with increasing Re_λ , for interwake turbulence in the final-decay period, which is just opposite to the behavior of conventional turbulence. The interwake region also involves rates of turbulence dissipation up to 1000 times larger than conventional turbulence at comparable outer scales, accounting for past problems of turbulence models to predict the properties of this flow (Lee et al. 2003).

The final phases of this study further considered the properties of laminar-like turbulent wakes and the turbulent interwake region for polydisperse (actually binary) particle phases (note that based on current understanding of effects of polydisperse particle phases, the extension of current findings for binary particle phases to polydisperse particle phases is trivial). These results indicated that the ambient turbulence level created by turbulence generation critically affected the properties of laminar-like turbulent wakes. This turbulence is in the final decay period, however, so that the nature of the particles used to create this turbulence is not critical, i.e., such flows do not have significant memories of the processes that formed them.

The other phase of this work considered the nature of length scales for turbulence generation properties in the final decay period. The first part of this work, however, actually considered grid-generated isotropic turbulence in the initial-decay period as a baseline. Present measurements of L_u/λ for these flows yielded values typical of earlier measurements of this ratio for grid-generated isotropic turbulence in the initial-decay period. These results also yielded the typical behavior of isotropic turbulence in the initial-decay period where L_u/λ increases with increasing values of Re_λ , i.e., the range of length scales in this flow increases with increasing Re_λ because the large scales are little affected by fluid viscosity (measured by Re_λ) whereas, the smaller scales become smaller with increasing Re_λ as a direct result of the scaling properties of the Kolmogorov microscale which is a measure of the smallest scales of turbulence.

Finally, an interesting trend of the final-decay period of isotropic turbulence found in the interwake region of turbulence generation processes is that the range of L_u/λ decreases with increasing Re_λ , which is exactly opposite to the behavior of conventional isotropic turbulence in the initial-decay period. This implies progressive reduction of L_u/λ with increasing Re_λ until this ratio approaches unity near $Re_\lambda \approx 20$, after which this ratio increases with increasing Re_λ typical of conventional isotropic turbulence. Work during the present report involved direct measurements of the energy spectra of isotropic turbulence in the final-decay period so that the range of the spectra could be observed directly. These results showed two things: (1) the range of the spectra became progressively smaller as L_u/λ approached unity, and (2) these spectra decay with increasing wave number according to the $-5/3$ power of the wave number as predicted by Kolmogorov for conventional isotropic turbulence more than fifty years ago.

Reexamination of the Kolmogorov derivation, however, revealed that properties of the final-decay period satisfied the assumptions of the initial-decay period equally well (the main requirement being the presence of a large range of length scales between the macro- and micro-scales of the turbulence). In this case, the ratio, L_v/λ , grows with decreasing Re_λ because the flow is dominated by sparse helical vortices whose axes are aligned in the streamwise direction. Then, the diameter of helix grows by the inviscid effect of induced vorticity whereas the scale of the microscales grows very slowly by viscous encroachments at small scales: the net effect is that the ratio L_v/λ increases with decreasing Re_λ , or what is the same with increasing distance from the particle source of the turbulence.

This behavior implies that turbulence essentially disappears at the transition condition at $Re_\lambda \approx 20$ where $L_v/\lambda \approx 1$. This region would be very interesting to observe but it is difficult to reach without providing ultra-low turbulent disturbances of the wind tunnel in the absence of particle flows. Naturally, at the start of the study we did not know enough about the flow to recognize this unusually stringent requirement; therefore, transition conditions were not achievable during the present study.

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Personnel Supported:

- G.M. Faeth, A.B. Modine Distinguished University Professor of Aerospace Engineering,
Principal Investigator
- C. Aalburg, Research Fellow
- F.J. Diez, Research Fellow
- K. Lee, Graduate Student Research Assistant
- K.A. Sallam, Research Fellow

Publications:

- Sallam, K.A. and Faeth, G.M., "Surface Properties During Primary Breakup of Turbulent Liquid Jets in Still Air," *AIAA J.*, Vol. 41, No. 8, pp. 1514-1524, 2003.
- Aalburg, C., van Leer, B. and Faeth, G.M., "Deformation and Drag Properties of Round Drops Subjected to Shock Wave Disturbances," *AIAA J.*, Vol. 41, No. 12, pp. 2371-2378, 2003.
- Lee, K., Chen, J.-H. and Faeth, G.M., "Properties of Particle-Generated Turbulence in the Final-Decay Period," *AIAA J.*, Vol. 41, No. 7, pp. 1332-1340, 2003.

Aalburg, C., Sallam, K.A., van Leer, B. and Faeth, G.M., "Properties of Nonturbulent Round Liquid Jets in Uniform Gaseous Crossflows," *Atom. Sprays*, in press.

Sallam, K.A., Aalburg, C. and Faeth, G.M., "Breakup of Round Nonturbulent Liquid Jets in Gaseous Crossflows," *AIAA J.*, in press.

Sallam, K.A., Aalburg, C., Faeth, G.M., Lin, K.-C., Carter, C.D. and Jackson, T.A., "Primary Breakup of Aerated-Liquid Jets in Uniform Gaseous Crossflow," *Atom. Sprays*, submitted.

Lee, K., "Turbulence Generation in Homogeneous Polydisperse Dispersed Particle-Laden Flows," Ph. D. Thesis, The University of Michigan, Ann Arbor, Michigan, in preparation.

Interactions/Transitions:

a. Participation/presentation at meetings, conferences, seminars, etc.:

Sallam, K.A., Aalburg, C., Faeth, G.M., Lin, K.-C., Carter, C.D. and Jackson, T.A., "Breakup of Aerated-Liquid Jets in Supersonic Crossflows," 42nd AIAA Aerospace Sciences Meeting, Reno, NV, AIAA Paper No. 2004-0970, 2004.

Aalburg, C., Sallam, K.A. and Faeth, G.M., "Properties of Nonturbulent Round Liquid Jets in Uniform Crossflows," 42nd AIAA Aerospace Sciences Meeting, Reno, NV, AIAA Paper No. 2004-0969, 2004.

Aalburg, C., Sallam, K.A., van Leer, B. and Faeth, G.M., "Properties of Nonturbulent Round Liquid Jets in Uniform Gaseous Crossflow," 56th Annual Meeting, American Physical Society, Division of Fluid Dynamics, Newark, NJ, 2003.

Sallam, K.A., Aalburg, C. and Faeth, G.M., "Experimental Study of the Breakup of Nonturbulent Round Liquid Jets in Gaseous Crossflow," 56th Annual Meeting, American Physical Society, Division of Fluid Dynamics, Newark, NJ, 2003.

Sallam, K.A., Aalburg, C., and Faeth, G.M., "Primary Breakup of Round Nonturbulent Liquid Jets in Uniform Gaseous Crossflows," *Proceedings of the 19th Annual Conference of ILASS Europe*, Nottingham, UK, 2004.

Sallam, K.A., Aalburg, C., Faeth, G.M., Lin, K.-C., Carter, C.D. and Jackson, T.A., "Primary Breakup of Aerated-Liquid Jets in Uniform Gaseous Crossflows," *Proceedings of the 19th Annual Conference of ILASS Europe*, Nottingham, UK, 2004.

Sallam, K.A., Aalburg, C., Faeth, G.M., Lin, K.-C., Carter, C.D. and Jackson, T.A., "Primary Breakup of Aerated-Liquid Jets in Uniform Gaseous Crossflows," *Proceedings of the 17th Annual Conference of ILASS Americas*, Washington, DC, 2004.

Aalburg, C., Faeth, G.M. and Sallam, K.A., "Primary Breakup of Round Turbulent Liquid Jets in Uniform Gaseous Crossflows," 43rd AIAA Aerospace Sciences Meeting, Reno, NV, submitted.

Aalburg, C., Lee, K., Faeth, G.M. and Sallam, K.A., "Experimental Study of the Breakup of Turbulent Round Liquid Jets in Gaseous Crossflows," 57th Annual Meeting, American Physical Society, Division of Fluid Dynamics, Seattle, WA, 2004.

Faeth, G.M., "Measurements of Primary Breakup Properties in Dense Sprays, 17th Annual Conference of ILASS-Americas, Washington, DC, 2004.

Faeth, G.M., "Primary Breakup Properties of Round Pure-Liquid and Aerated-Liquid Jets in Gaseous Crossflows," AFOSR/ARO Contractors' Meeting in Chemical Propulsion, Tucson, AZ, 2004.

b. Consultation and Advisory Functions.

A paragraph describing my interactions with AFRL Researchers during the past year is as follows:

Meetings at the start of the present investigation between C. Carter and T.A. Jackson of the Propulsion Directorate of AFRL at Wright-Patterson Air Force Base, OH, Steven Lin of Taitec, Inc., Beavercreek, OH and individuals at the University of Michigan, Ann Arbor, MI, developed a collaboration to study the primary breakup properties of aerated-liquid injectors in supersonic crossflow. There were two main objectives of the planned research, as follows: (1) to develop an improved pulsed holocamera that would have the capability to penetrate the dense spray region right up to the liquid surface and allow observations of the mechanisms and outcomes of primary breakup, and (2) to apply this technology to gain a better understanding of the primary breakup properties of aerated-liquid jets in supersonic crossflows. Given the experience of the AFRL personnel with laser-based optical diagnostics, pulsed holography techniques developed at the University of Michigan were substantially modified to obtain an improved holocamera system. The new holocamera was then used to observe the primary breakup properties of aerated-liquid jets for the large liquid/gas-density ratio and supersonic crossflow conditions of interest for missile propulsion system applications. Phenomenological analyses were used to help interpret and correlate the measurements for use by others. These observations have defined the topography of the flow, have provided some of the primary breakup properties of the flow, and have shown that the effect of even a supersonic crossflow on aerated-liquid breakup is relatively weak. These results have been summarized in a paper that has been submitted for publication (K.A. Sallam et al., "Primary Breakup of 'Aerated-Liquid Jets in Supersonic Crossflow," *Atomization and Sprays*, submitted). This collaboration involved several meetings per month at either AFRL, Wright-Patterson AFB, OH or the Department of Aerospace Engineering at the University of Michigan, Ann Arbor, MI.

c. Transitions

There were two activities of this nature during the report period, as follows:

Customer:

Dr. Hakam Mongia
Manager, Advanced Combustors Engineering
GE Aircraft Engines (GEAE)
One Neuman Way, MDE404
Cincinnati, OH 45215-1988

Subject Matter:

This involved transferring recent information developed during the currently-active grant concerning the breakup of round

nonturbulent liquid jets in gas crossflows to GEAE. This information is being used to develop numerical simulations of the combustion systems of propulsion devices.

Customer:

Dr. David Hagen
VAST Power Systems, Inc.
Value-Added Steam Technologies
2824 South 17th Street
Elkhart, IN 46526-8713

Subject Matter:

This involved transferring recent information developed during the currently-active grant concerning the breakup of round aerated-liquid jets in supersonic air crossflow and also the breakup of round nonturbulent and turbulent liquid jets in gaseous crossflows to VAST Power Systems, Inc. This information is being used during the development of novel liquid-fueled combustion systems for power generation.

New Discoveries, Inventions or Patent Disclosures:

None

Honors/Awards:

a. During Grant/Contract Period (for G. M. Faeth):

Invited Plenary Lecture, "Mechanics of Fire Suppression by Halons and Halon Replacements," 6th International Conference on Technologies and Combustion for a Clean Environment," Porto, Portugal, 2001

Medal of Appreciation, Helwan University, El Mattaria, Cairo, Egypt, 2002

Invited James E. Peters Plenary Lecture, "Optical and Radiative Properties of Soot in Flame Environments," Spring Technical Meeting, Central States Section, The Combustion Institute, Pittsburgh, 2002

Invited Distinguished Lecture, "Soot Growth and Oxidation Properties of Premixed and Nonpremixed Flames," Dept. Chem. and Fuels Engr., University of Utah, 2002

Invited Plenary Lecture, "Soot Formation and Oxidation in Premixed and Nonpremixed Flame Environments," Spring Technical Meeting, Canadian Section, The Combustion Institute, Pittsburgh, 2002

Invited 2002 Distinguished Lecture, "Mechanisms of Fire Suppression by Halons and Halon Replacements," Mechanical Engineering and Mechanics Dept., Drexel University, Philadelphia, PA, 2002

Invited Plenary Lecture, "Properties of Postflame (Overfire) Turbulent Plumes in Still and Crossflowing Environments," 8th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, St. Louis, MO, 2002

Invited Plenary Lecture, "Dynamics of Secondary Drop Breakup — A Rate Controlling Process in Dense Sprays," ILASS-Europe 2002, Zaragoza, Spain, 2002

Invited Andrew H. Hines, Jr. Lecture, "Turbulence Generation by Drops in Sprays," Dept. Mech. Aero. Engr., University of Florida, Gainesville, FL, 2002

Fellow, American Physical Society (APS), 2003

National Associate (National Academy of Sciences, National Academy of Engineering, Institute of Medicine, National Research Council), 2003

Space Processing Award, American Institute of Aeronautics and Astronautics (AIAA), 2004

Alfred C. Egerton Gold Medal, The International Combustion Institute, 2004

Arthur B. Modine Distinguished University Professor of Aerospace Engineering, The University of Michigan, 2004

b. Lifetime Achievement Awards (all for G.M. Faeth):

Outstanding Achievement in Research Award, College of Engineering, The Pennsylvania State University (1979)

Fellow, ASME (1983)

Heat Transfer Memorial Award, ASME (1988)

Excellence in Research Award, College of Engineering, University of Michigan (1988)

Fellow, AIAA (1988)

Outstanding Engineering Alumnus, The Pennsylvania State University (1990)

Fellow, AAAS (1990)

Member, National Academy of Engineering (1991)

Distinguished Engineering Faculty Research Award, University of Michigan (1992)

Propellants and Combustion Award, AIAA (1993)

Stephen S. Attwood Award, University of Michigan (1993)

NASA Public Service Medal (1999)

Silver Shaft Award, Sigma Gamma Tau, The University of Michigan (2000)

Highly-Cited Researcher Certificate (for being among the 99 most-cited engineers in the world), Institute for Scientific Information (2000)

Medal of Appreciation, Helwan University, Cairo, Egypt (2002)

Fellow, APS (2003)

National Associate, National Academy of Engineering (2003)

Space Processing Award, AIAA (2004)

Alfred C. Egerton Gold Medal, The International Combustion Institute (2004)