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RADIATION EFFECTS ON FLOW CHARACTERISTICS IN COMBUSTION CHAMBERS*

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ASTRACT

A JANNAF sponsored workshop was held in conjunction with the AIAA/ASME/SAE Joint Propulsion Conference at Monterey, CA on July 11, 1989 to discuss the importance and role of radiative heat transfer in rocket combustion chambers. The potential impact of radiative transfer on hardware design, reliability and performance was discussed. The current state of radiative transfer prediction capability in CFD modeling was reviewed and concluded to be substantially lacking in both the physical models used and the radiative property data available. There is a clear need to begin to establish a data base for making radiation calculations in rocket combustion chambers. A natural starting point for this effort would be the NASA thermochemical equilibrium code (CEC).

INTRODUCTION

A JANNAF sponsored workshop was held in conjunction with the AIAA/ASME/SAE Joint Propulsion Conference at Monterey, CA on July 11, 1989 to discuss the importance and role of radiative heat transfer in rocket combustion chambers. Participants in the workshop included representatives from academia, industry and government, as noted at the end of this report. Due to the growing recognition of the influence of radiative transport on many key processes occuring in rocket combustion chambers, the scheduling of this workshop was felt to be timely and well justified.

There are several significant sources of radiation in a rocket combustion chamber and several significant sinks which are affected by radiant energy received from these sources. The primary sources of thermal radiation are the hot combustion products, which may include molten aluminum oxide particles, soot and molecular gases. The primary sinks of thermal radiation are the vaporizing liquid droplets, the chamber wall or insulator surfaces, and, in liquid rockets, the injector plate. Due to convective and radiative heating by the combustion products, the chamber wall itself may also become a significant source of thermal radiation for heating and vaporizing liquid droplets which are within a few mean free photon pathlengths of the wall. Thus there is a variety of radiative transfer mechanisms within rocket combustion chambers which may influence the microscopic physical processes occuring within the chamber and therefore ultimately the macroscopic performance of the engine or motor.

PURPOSE

The purpose of this workshop was to assess the potential impact of radiative transfer on several key aspects of rocket combustion chamber behavior including,

1. Hardware design (economy, life cycle fatigue, materials, and cost)
2. Performance prediction
3. Spray flowfield, fluid mechanics, thermodynamics and radiation prediction
4. Combustion instability (future potential).

The specific objectives of the workshop were as follows:

1. Formulate a statement of present radiation simulation capability
2. Specify and prioritize physical processes affected by radiation
3. Establish criteria for importance of radiation
4. Give guidance for radiation modeling in CFD codes
5. Suggest experiments and significant measurements to be made

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* Approved for public release; distribution is unlimited.

FORMAT

The format of the workshop was a series of presentations followed by open discussion of the topics. Presentations were made by the respective participants as indicated below:

Overview of Rocket Performance and Design	Klaus Gross
Overview of Radiation Effects in Combustion Chambers	Quinn Brewster
Radiation Effects on Rocket Engine Performance	Paul Chiu
Radiation Modeling in Rocket Thrust Chambers	Homayun Kehtarnavaz
Estimation of Radiation Energy Absorption by Liquid Fuel Droplets and its Effects	S. S. Cha
Radiative Flux from Soot Particulates and Molecular Gases	Don Edwards and Scott Samuelsen
Radiative Properties of Burning Al and Molten Al_2O_3 Particles	Quinn Brewster
Radiation Modulated Spray Combustion	Paul Chiu

After the presentations were given an open discussion was held and the following summary represents the conclusions and recommendations reached by the workshop participants in reponse to the stated workshop objectives.

WORKSHOP RESULTS

1. STATEMENT OF PRESENT RADIATION SIMULATION CAPABILITY

With regard to gas radiation calculations there is a wide range of levels of sophistication currently available in analytical modeling, including:

a. Line-by-line calculations,
b. Narrow band models,
c. Wide band models, and
d. Emissivity models.

with level of complexity increasing from (a) to (d). For the rocket combustion chamber application it was concluded that almost no set of circumstances would justify line-by-line calculations. For most situations where gas radiation was of significance (i.e. non-metallized propellants) either a band model or k-distribution approach would be the method of choice. The band models are more popular but cannot easily incorporate scattering effects in a rigorous fashion. The k-distribution approach, however, which has been developed in the field of atmospheric radiation, has the advantage of being able to incorporate scattering effects rigorously and appears to be well enough developed to merit consideration in the rocket chamber application.

With regard to particulate radiation properties, Mie theory (and the limiting cases of Rayleigh scattering and geometric optics, as appropriate) are well accepted and appropriate for simulating the spherical and randomly oriented non-spherical particles in a rocket combustion chamber. Figure 1 shows a typical comparison of the absorption efficiency for a spherical water droplet at 1.2 µm calculated by Mie theory and geometric optics. Many effective schemes have been demonstrated for replacing the rigorous anisotropic Mie scattering properties with effective isotropic scattering properties, and this technique should be entirely appropriate for application in rocket combustion chambers when scattering effects are important (i.e. metalized propellants).

As far as the transfer part of the problem is concerned, the radiative transfer equation is generally recognized as the appropriate mathematical framework for solving the problem. The transfer equation is an optical energy balance on a single scattering, optically thin volume element along a single line-of-sight, as pictured in Fig. 2. The transfer equation is coupled to the energy equation through the source function for thermal emission, which, for a medium in local thermodynamic equilibrium, is the Planck function. For each volumetric element, the transfer equation must be solved for all directions, in some appropriate coordinate system, as shown in Fig. 3. Thus, the transfer equation solution involves three distinct integrations: (1) directional, (2) spatial, and (3) spectral.

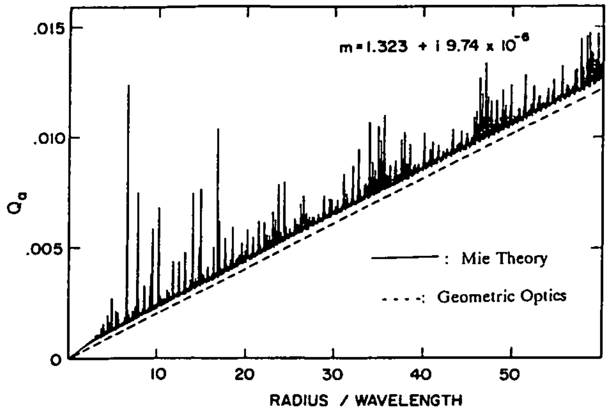
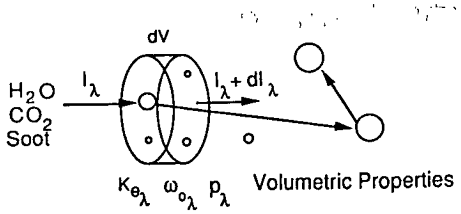


Fig. 1 Comparison of Mie and geometric optics absorption efficiencies for water droplet at 1.2 μm



Extinction Coefficient $K_{e_\lambda} = \frac{4\pi k(1-f_v)}{\lambda} + \frac{1.5 f_v \overline{Q} e_\lambda}{d_{32}}$

Homogeneous Medium (Gas) — Particulate

Albedo $\omega_0 = \frac{K_s}{K_e}$

Optical Depth $t_\lambda = \int K_{e_\lambda}\, ds$

(E) $\rho \frac{Dh}{Dt} = -\nabla \bullet (q_c + q_r) + \Phi + \frac{DP}{Dt}$ (multi-phase, multi-component)

(Tr) $\frac{1}{K_{e_\lambda}} e_\Omega \cdot \nabla I_\lambda(\Omega) = -I_\lambda(\Omega) + \sum_{\text{soot, gas, drops}} (1-\omega_{o_i})\, I_{b_\lambda}(T_i) + \frac{\omega_o}{4\pi}\int_{4\pi} I_\lambda(\Omega')\, p_\lambda(\Omega,\Omega')\, d\Omega'$

$q_{r_i} = \int_0^\infty \int_{4\pi} I_\lambda\, e_\Omega \cdot e_i\, d\Omega\, d\lambda$

→ The mathematical formalism for radiative transfer is well-established; calculations (e.g. Monte Carlo) are tedious.

→ Correlated gas band properties are not well suited for including scattering or non-isothermal effects

Fig. 2 Radiative transfer equation as an optical energy balance on a single-scattering, optically thin volume element

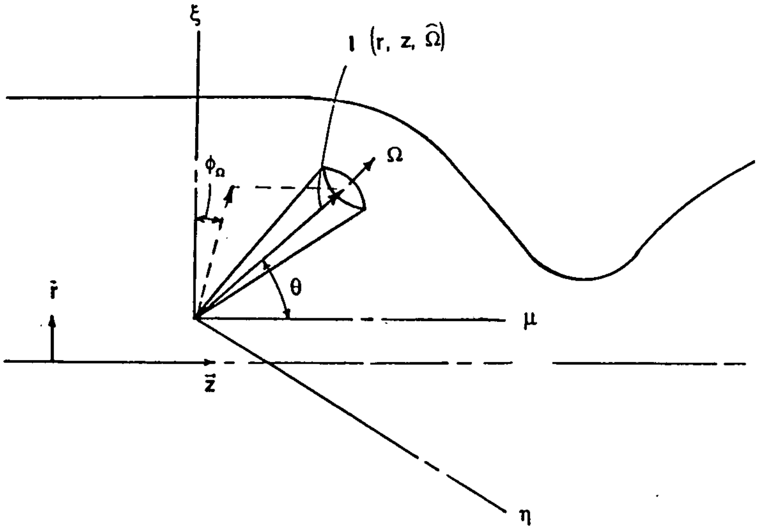


Fig. 3 Radiative transfer equation in a rocket chamber geometry

Various levels of sophistication exist for solving the transfer equation, depending on the application, including:

a. Monte Carlo simulation
b. A series of equivalent numerical approximations including
   i. Method of discrete ordinates
   ii. P_N approximation
   iii. Moment method, etc.
c. Flux methods (2-flux, 6-flux, etc.)

Several codes (such as ELLPAK) have been developed for solving the transfer equation. It was noted by Kehtarnavaz that a significant computational savings could possibly be realized by solving the transfer equation using the P_N approximation wherein the uncertainty or approximation is shifted to the boundary conditions, requiring only iterations on the boundaries and not over the entire flowfield. This method may prove to be particularly attractive for coupled radiation-flowfield calculations.

In addition to these classical approaches some novel techniques have also been developed recently such as Edwards' hybrid Monte Carlo-matrix inversion technique (PARRAD), which combines fast-running Monte Carlo calculations with a zonal interchange analysis to model rocket plume heat transfer. Another very recent approach is that suggested by Chiu which represents the radiative flux vector as the gradient of a scalar potential function and invokes the mathematical formalism of potential theory to solve the radiative transfer problem.

The other aspect of current radiation simulation capability which was discussed, in addition to fundamental radiation calculations as noted above, was the capability of simulating fully coupled flow and radiation fields. The coupling of the transfer equation to the energy and flow equations generally requires an iterative procedure to obtain a solution, as indicated schematically in Fig. 4. It was concluded that at the present the availability of CFD codes which can do fully coupled radiation flowfield calculations covering a wide range of opacities, including scattering and non-gray gas properties is virtually non-existent. Some limited capability exists in the form of gray media and optically thin or optically thick limits. For example, FLUENT (an Eulerian-Lagrangian scheme) incorporates a gray, six-flux model. However, this model requires that the effective gray absorption and scattering coefficients for the gas phase be input by the user instead of calculating them from first principles for the species present. Furthermore, FLUENT's radiation model does not provide for direct radiative interaction with the particle phase which is usually the dominant participator if present. Other CFD codes identified which are under development to include some form of radiative transfer are CELMINT, which is an Eulerian-Lagrangian scheme, and GEMCHIP, an Eulerian-Eulerian treatment.

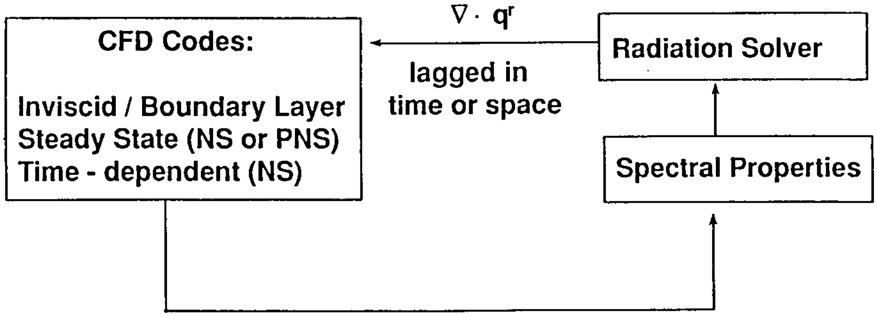


Fig. 4 Iterative solution required for coupled radiative transfer and flow equations

Several other areas of science and technology were also identified with developed or developing combined flowfield radiative transfer simulation capability which should be viewed as additional sources from which to extract information and modeling guidance. These areas include laser propulsion, atmospheric circulation modeling, internal combustion engines, jet engines (NASP), and the utility boiler industry.

2. PHYSICAL PROCESSES AFFECTED BY RADIATION

Four physical processes were identified as being affected by radiative transfer and prioritized as follows:

A. Wall heat flux
B. Liquid droplet radiation interaction
C. Turbulence radiation interaction
D. Radiation combustion stability interaction

Wall Heat Flux. The additional heat flux to the combustion chamber wall was viewed as the most important radiation affected process. The most severe situation in this regard, potentially, is that of RP1-aluminum slurries which are currently being envisioned for liquid boosters in order to increase the density of the propellant. The radiative heat flux to the chamber wall could increase by orders of magnitude over that for conventional propellants if aluminum is burned in the combustion chamber, due to the strongly emitting and scattering molten aluminum oxide particles and burning aluminum droplets. The next most severe case is that of sooting propellants (e.g. RP1-LOX) which produce radiant flux levels which are probably about an order of magnitude below that of metalized propellants, but which are still very significant due to the soot continuum contribution. The least severe case in terms of radiative flux is that of non-sooting propellants with no condensed phase products, (e.g. LH_2-LOX) where the radiative contribution comes solely from infrared active molecular gases. Even this least severe case, however, could result in significant radiant flux levels (due to the high pressures and strong line broadening) which may easily be overlooked or underestimated as in the base heating problems of the early days of the space program.

The radiative heat flux to the wall is not only of interest for reasons of structural integrity, life cycle, and fatigue, but is also of interest because of performance considerations. For example, radiative flux may play an augmentive role in the context of expander cycles which are being considered for utilizing thermal energy from the boundary layer to power turbopumps. These cycles would improve performance by eliminating pre-combustors and it is possible that a significant component of radiant flux to the chamber wall may influence the system design and performance. On the other hand, the portion of radiative heat flux to the wall which cannot be recovered by either an expander cycle or a conventional regenerative cycle represents a loss and may result in a decrease in the overall system performance. As an illustration of this point, Chiu presented calculations of engine performance using typical regenerative heat recovery efficiencies, for non-sooting propellants, which showed that the performance of low enthalpy engines, such as the Variable Thrust Engine (VTE) could be significantly affected by unrecovered radiative loss to the wall, whereas higher enthalpy engines, such as the Space Shuttle Main Engine (SSME), were not as susceptible to performance degradation, at least for non-sooting propellants.

Liquid Droplet Radiation Interaction. The second physical process of importance considered was the radiation droplet interaction. Thermal radiation, originating from either the hot combustion products directly or indirectly from the heated chamber wall could enhance the vaporization and combustion rates of liquid propellant droplets. This process would influence engine performance by increasing vaporization and combustion efficiency. A related issue of a more specific nature is whether droplets traveling toward the heated combustion chamber wall actually impact the wall or not. In the VTE, fuel droplets (MMH) are intentionally sprayed toward the wall to enhance the film cooling effect. It is uncertain, however, if the droplets vaporize before impacting the wall. The wall itself is heated to a glowing yellow, incandescent state, partly due to significant radiation from the MMH-N_2O_4 gaseous combustion products. Therefore, the radiative energy from the wall may be an important factor which needs to be included in considering the evaporation rate of the droplets as they approach the wall.

Turbulence Radiation Interaction. The third physical process of potential significance is the interaction between radiation and turbulence. This interaction could lead to enhanced mixing, enhanced atomization via metastable vapor explosions (microexplosions) and modification of the important transport properties such as thermal and momentum diffusivities. Of unique interest in the radiative transport area is the possibility of time-correlation of fluctuating quantities at spatially remote locations. Such correlation between properties at spatially remote locations is not possible in the usual framework of conductive-convective energy transport but only becomes possible with the radiative transport mechanism.

Radiation Combustion Stability Interaction. Finally, a fourth area identified for potentially significant interaction is the area of radiation-combustion stability. This area is obviously related to the physical processes of droplet-radiation interaction and turbulence-radiation interaction but is listed separately to emphasize the unsteady aspects of these interactions as opposed to the time-averaged, psuedo-steady effects. Of particular significance is the fact that relaxation times for radiative transfer are essentially zero compared with those of the conductive-convective energy transport associated with even the most intense turbulent, recirculating flow. Also of significance is the fact that in those circumstances where radiative transfer is expected to be particularly strong (metalized and sooting flows) the radiative emission process is not a very strongly pressure-coupled process which means that the radiative transfer process could exert a significant pressure-decoupling influence on acoustically coupled unsteady combustion. Clearly there is need for more evidence and thus more investigation in this area before a definitive assessment can be made. A lower priority was assigned to this area pending the outcome of a separate workshop which is addressing the instability issue exclusively. This lower priority does not reflect the relative importance of this phenomenon so much as the fact that the issue is being addressed by a separate workshop.

3. CRITERIA FOR IMPORTANCE OF RADIATION

The purpose of this exercise was to identify appropriate parameters (non-dimensional, if possible) which could be evaluated to establish the relative importance of radiative transfer effects. This was done with respect to each of the first three physical processes which were identified and prioritized above.

- Wall Heat Flux. The most obvious parameter to assess the relative importance of radiative transfer in this case is the ratio of the radiative flux at the wall to the total heat flux.

$$\frac{q_{wr}}{q_{wr}+q_{wc}} \gtrsim 0.1 \quad \rightarrow \text{ radiative transfer significant}$$

However evaluation of this parameter is not straightforward and requires more detailed consideration of the radiation and flow fields. The most difficult aspect of this process is estimating the radiative flux (the convective flux can be estimated by ignoring radiative transfer effects and using well known correlations).

The radiative flux can be estimated by evaluating a few key radiative parameters and using a simple model of the radiative transfer. The most important parameter which should be evaluated first is the optical thickness based on thermal boundary layer thickness, $t_{\delta T}$.

$t_{\delta T} > 1$, optically thick boundary layer
$t_{\delta T} < 1$, optically thin boundary layer

Strictly speaking this parameter is a spectral quantity and should be considered on a spectral basis. In particular, for gas dominated radiation, a spectral analysis is required even for this approximate evaluation. However, for soot or Al_2O_3 dominated radiation a gray analysis is suitable for this initial approximate analysis.

The approach taken depends on whether the thermal boundary layer is optically thick or thin. The optically thick boundary layer case will be illustrated first. This will be done for a gray medium.[1] In the case of an optically thick boundary layer ($t_{\delta T} > 1$), the diffusion approximation holds and the relative importance of radiation can be expressed in the form of a Rosseland averaged radiation-conduction parameter,

$$N = \frac{k\, K_{eR}}{4\, \sigma\, T^3} < 1, \text{ radiation dominated transport}$$

$$N = \frac{k\, K_{eR}}{4\, \sigma\, T^3} > 1, \text{ conduction dominated transport}$$

where k is the fluid thermal conductivity, K_{eR} is the Rosseland mean extinction coefficient, σ is the Stefan-Boltzmann constant, and T is a characteristic temperature of the boundary layer. In this situation the conduction-radiation parameter can be thought of as a ratio of conductive flux (or thermal conductivity) to radiative flux (or radiative conductivity). It should be noted, however, this interpretation does not hold in the optically thin limit[2].

Another parameter of importance in the optically thick boundary layer limit is the radiation modified Prandtl number, which arises out of the viscous fluid flow equations when radiation diffusion is incorporated.

$$Pr_r = \frac{Pr}{1 + \frac{4}{3N}} >> 1, \ \delta_T << \delta \text{ (hydrodynamic B.L. thickness)}$$

$$Pr_r = \frac{Pr}{1 + \frac{4}{3N}} << 1, \ \delta_T >> \delta$$

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[1] The only case where there is a reasonable possibility of encountering an optically thick boundary layer ($t_{\delta T}$>1) is in highly aluminized propellants, and the properties of the prinicipal participator in that case (molten Al_2O_3) can be approximated as gray for this evaluation. When gas radiation dominates it is unlikely that the thermal boundary layer would be optically thick over a significant portion of the spectral region of interest. In that event, however, a spectral analysis would be necessary.

[2] That this is so can be seen by considering the limit $K_e \rightarrow 0$ for the hypothetical gray case ($K_{eR} = K_e$). In this limit $N \rightarrow 0$, which would indicate radiation dominated transport, but clearly the heat flux is not radiation dominated in the optically thin limit.

The significance of noting this parameter is that for radiation dominated, optically thick transport ($N \ll 1$, $t_{\delta T} > 1$) the flow will behave like that of a low Prandtl number fluid, since the fluid Prandtl number is typically of order unity in rocket chambers. Thus the thermal boundary layer thickness will be much larger than the hydrodynamic boundary layer thickness and this fact should be taken into consideration in estimating $t_{\delta T}$.

In the case of an optically thin boundary layer ($t_{\delta T} < 1$), the radiative flux to the wall depends on the radiative properties of the core flow. For purposes of estimating the radiative flux the core flow can be assumed to be isothermal at an effective core temperature T_C.

For an optically thin chamber ($t_L<1$) and optically thin boundary layer ($t_{\delta T} < 1$) the non-dimensional radiative flux to a non-emitting, non-reflecting wall[1] from a gray medium can be estimated from the limiting solution

$$\left(\frac{q_{wr}}{\sigma T_C^4}\right)_{\varepsilon_w=1,\, T_w=0} = (1-\omega_{ol})\, t_L\,, \quad (t_L<1 \text{ and } t_{\delta T} < 1)$$

where L is the characteristic chamber dimension (diameter) and ω_{ol} is the effective isotropic single scattering albedo or one minus the particle emissivity. It should be noted that neither ω_{ol}, i.e. particle emissivity, nor chamber length scale were important parameters in the optically thick boundary layer case.

For an optically thick chamber ($t_L>1$) and optically thin boundary layer ($t_{\delta T} < 1$) the non-dimensional radiative flux can be estimated from any of a number of approximate solutions to the radiative transfer equation, such as the two-flux model, which gives

$$\left(\frac{q_{wr}}{\sigma T_C^4}\right)_{\varepsilon_w=1,\, T_w=0} = \frac{1-\omega_{ol}}{\omega_{ol}}\left\{\left(1 + \frac{2\omega_{ol}}{1-\omega_{ol}}\right)^{1/2} - 1\right\}, \quad (t_L>1 \text{ and } t_{\delta T} < 1)$$

These relations are general in the sense that they cover all cases of Al_2O_3, soot, or gas dominated radiation in the optically thin boundary layer limit. For aluminized propellants the magnitude of $1-\omega_{ol}$ is on the order of 10^{-2} to 10^{-1}. For soot or gas dominated radiation ω_{ol} can be taken as zero (non-scattering medium).

The process of assessing the relative importance of radiation on wall heat flux, can be summarized in the following steps:

- estimate δ_T and q_{wc} based on convective analysis of non-radiating flow
- estimate $t_{\delta T}$
- if $t_{\delta T}>1$, estimate N to determine importance of radiation (modify $t_{\delta T}$ if $N \ll 1$)
- if $t_{\delta T}<1$, estimate $\frac{q_{wr}}{q_{wr}+q_{wc}}$ to determine importance of radiation.

Liquid Droplet Radiation Interaction. The effects of radiative heat transfer can be readily incorporated into the classical diffusion-limited, droplet combustion (or evaporation) theory. The resulting parameter of importance is the ratio of the radiation augmented transfer number (or B-number) to the non-radiative value, as demonstrated by Chiu,

$$\frac{B_r}{B} = \frac{1}{1 - \frac{Q_r}{\dot{m}L}}$$

where Q_r is the net radiative transfer to the droplet, $\dot{m}$ is the mass evaporation rate, and L is the latent heat of vaporization. It can be seen that the effect of radiative heat transfer to the droplet is to increase the combustion or vaporization rate through an increase in B-number. Evaluation of the radiation augmented B-number requires an estimate of the radiative transfer to the droplet. For these purposes liquid hydrocarbon and liquid oxygen droplets can probably be taken as non-emitting in most cases and the net radiative heat transfer will be equal to the rate of radiant energy absorption. The rate of energy absorption will be influenced significantly by the optical properties of the droplet and the surrounding radiative environment. A typical calculation of the ratio of the radiative to conductive heat flux to a burning hydrocarbon droplet in a blackbody environment is shown in

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[1] Wall emission and reflection effects can be incorporated using the superposition principle.

Fig. 5. The radiative component increases as the droplet size and radiative environment temperature increase. While thermal emission by a burning hydrocarbon droplet may be small, in the case of a burning metal droplet, emission by the molten metal may not be insignificant due to the higher droplet temperatures. Furthermore, the detached, oxide-laden flame envelope surrounding the droplet will be a significant source of thermal radiation influencing the flux to the droplet in the case of metals.

Other parameters which may be of significance in the droplet radiation interaction are the radiation modified Damköhler number and the ignition delay time. However, no explicit relationships for these parameters were given.

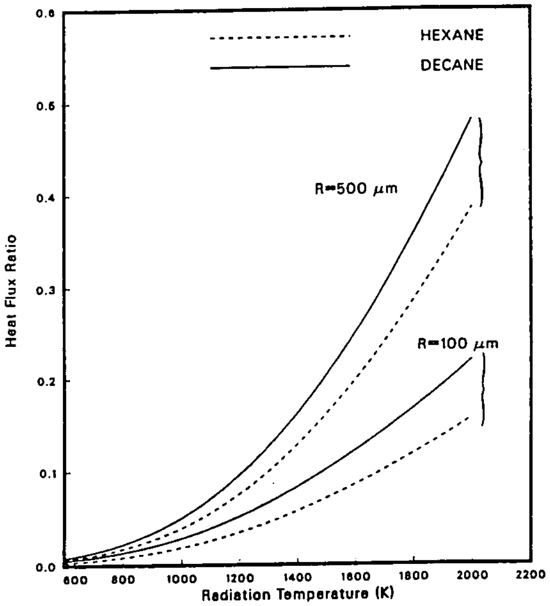


Fig. 5 Ratio of radiative to conductive heat flux to hydrocarbon droplet as a function of environment radiative temperature

Turbulence Radiation Interaction. There are several parameters which may be of importance in assessing the influence of radiative transport on turbulence. Most of these parameters can be expressed in the generic form of a correlation parameter S, according to Chiu. For example $S_{\alpha-\alpha}$ describes the time-correlation between fluctuating absorptivity (or absorption coefficient) at two locations (i.e. eddies) which are spatially remote but within a few mean free photon paths and can thus interact with each other radiatively. Similarly $S_{\alpha-I_b}$ describes the correlation between absorptivity and Planck function (or temperature) between two turbulent eddies. There are a variety of these correlation parameters which arise out of the time-averaged turbulent energy equation when radiative transport is included and it remains to be demonstrated which ones, if any, are important.

Another parameter which was suggested as being representative of the overall importance of radiation-turbulence interactions is the optical depth based on eddy length scale. Presumably there would be some minimal value this parameter must assume before correlations between fluctuating radiative and flow field properties could significantly influence the mean flow.

4. GIVE GUIDANCE FOR RADIATION MODELING IN CFD CODES

The kind of description which is appropriate to use in modeling radiative transfer in a rocket combustion chamber depends on many chamber variables and it is impossible to prescribe one general approach which is equally useful for all cases. It is useful to therefore differentiate initially between metalized and non-metalized propellants, because the radiative environments are so different between these two cases.

Non-metalized Propellants. The dominant sources of radiation which would need to be accounted for in this case are soot and infrared active molecular gases. It was pointed out that these sources are not generally in thermal equilibrium, since the soot is oxidizing, and it may be appropriate to account for the difference in temperature between these two sources of radiation. Figure 6 shows typical results for thermal emission by a sooting hydrocarbon flame with soot contribution shown by the Planck-like continuum and the molecular gas bands represented as equivalent black rectangles using a wide band model. Comparing Figs. 6a and 6b shows that as the soot optical depth t_s increases, due to an increase in pressure, the soot contribution and the

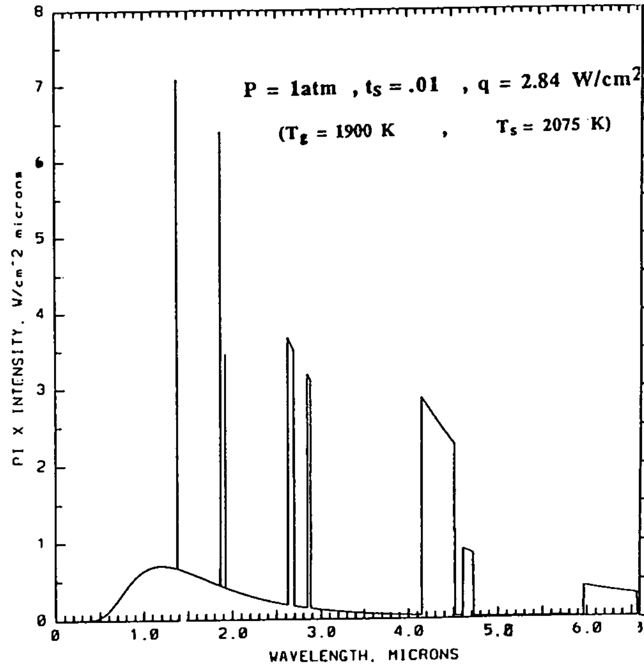


Fig. 6a Relative contribution of soot continuum and molecular gas band radiation for low pressure

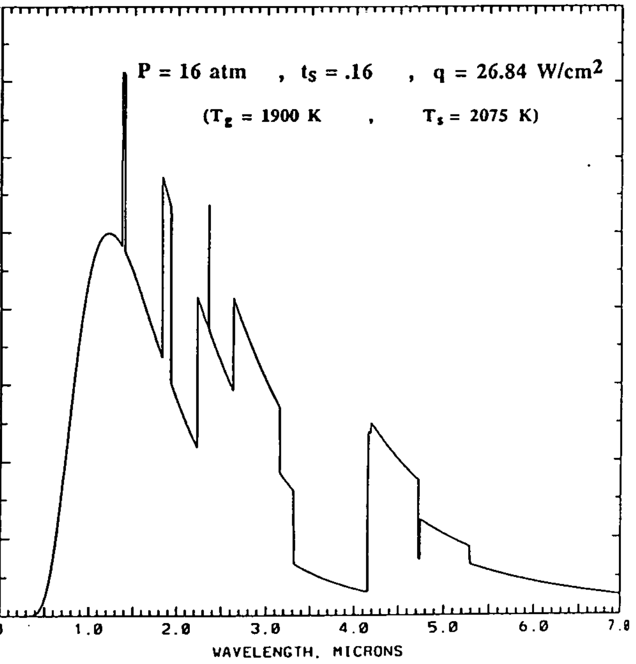
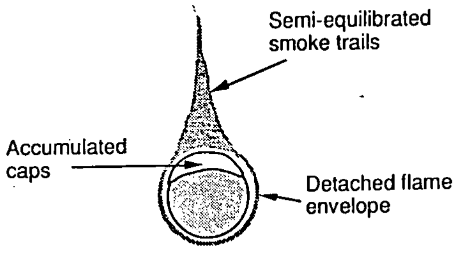


Fig. 6b Relative contribution of soot continuum and molecular gas band radiation for high pressure

total heat flux increase significantly. For modeling the soot radiative properties Mie theory still seems to be the widely accepted approach and for modeling the gas properties band models would seem to be appropriate with a Curtis-Godson scaling to account for non-homogeneous effects. Although emission by liquid droplets could probably be neglected, absorption by the droplets should be included using either Mie theory or geometric optics results, as appropriate. There was some discussion as to whether scattering effects would be important in non-metalized propellant flows. The tentative conclusion was that it would probably depend on the size of the droplets and the scattering mean free photon path. For large size parameters ($\pi d/\lambda >> 1$) the scattering (both the diffracted and refracted components) would be so forward directed that a non-scattering treatment might be justifiable if the mean free photon path for scattering was large compared with the chamber dimensions (optically thin for scattering). For those circumstances where scattering is important it was recommended that the method of solving the transfer equation be selected as appropriate to the situation, depending on whether the medium of interest was optically thin, thick or intermediate. In the latter case a variety of solution techniques



$n \sim 1.65$ $k \sim 10^{-3}$ to 10^{-2} → lossy, non-conductive dielectric

Size, d (μm)	10^{-2} to 10^{-1}	1	10 to 100
Source of particles	Detached flame envelope	Semi-equilibrated smoke trails	Caps from surface accumulation
Size parameter $\frac{\pi d}{\lambda}$	<<1	~1	>>1
Radiative scattering regime	Rayleigh	Mie	Geometric Optics
Particle emissivity	0.5 - 1	0.03 - 0.06	$\frac{4n}{(n+1)^2} \sim 0.94$
Extinction efficiency	10^{-5} - 10^{-3}	2 - 4	2 (1)

Fig. 7 Summary of aluminum oxide particle radiative properties

were mentioned including Edwards' hybrid Monte Carlo-matrix inversion method, the P_N approximation, the discrete ordinate method, and the potential theory of Chiu.

Metalized Propellants. For metalized propellants it was recognized that Al_2O_3 participation would dominate the radiative transfer in most cases and that scattering would indeed need to be incorporated. The optical properties of aluminum oxide are summarized in Fig. 7, which emphasizes the strong effect of particle size. Sub-micron smoke particles produced in the detached flame envelope of a burning aluminum droplet might have relatively high "particle emissivities" but low extinction efficiencies due to Rayleigh scattering characteristics. Micron-sized particles which have resulted from agglomeration of the smaller sub-micron particles would have relatively low "particle emissivities" but much larger extinction efficiencies. And large caps produced by surface combustion would have high emissivities and large efficiencies. Thus, the analytical formulation of aluminum oxide radiative properties conceivably could be very complicated, covering the entire particle scattering regime from Rayleigh scattering to geometric optics. Gas and soot radiation may or may not be significant depending on the level of metal loading. For low metal loadings gas and soot radiation may also need to be included. The choice of the method of solving the transfer problem should again be appropriate to the opacity of the medium.

5. EXPERIMENTS AND MEASUREMENTS NEEDED

There are two types of measurements which are needed, (1) fundamental material property measurements and (2) system property measurements.

Fundamental Material Property Measurements Needed. Considering first gases, the type of properties required depends on the level of description used in the modeling. The band model approach uses line intensity, line spacing and line width as the fundamental properties (on a narrow band basis) or band intensity, bandwidth and line overlap (on a wide band basis). These properties need to be known for the gases of interest over the temperature and pressure ranges of interest. Although there is a substantial data base available for these gases at pressures below 150 psi and temperatures below 2000 K it was felt that there was a need for measurements at higher temperatures and pressures so that the need for theoretical extrapolation could be eliminated (or at least the accuracy of doing so verified).

Considering next liquids, the fundamental material properties of interest are the optical constants n-ik. Measurements of these properties are urgently needed for RP1, LOx, LH_2, MMH, N_2O_4, and CH_4 for temperatures and pressures up to the critical point. There is also a need for measurements at supercritical temperatures and pressures.

System Property Measurements Needed. The system property measurements required are those properties, other than the fundamental material properties, which also determine the local volume-based radiative properties of the medium (such as extinction coefficient). These properties include volume fractions (spatially resolved) of soot, liquid droplets, and Al_2O_3 particles for various flow configurations and combustion chamber operating conditions. Also the size distributions of these same condensed phase participators is required. These data are needed as input to the radiative transfer subroutine of any given flowfield model.

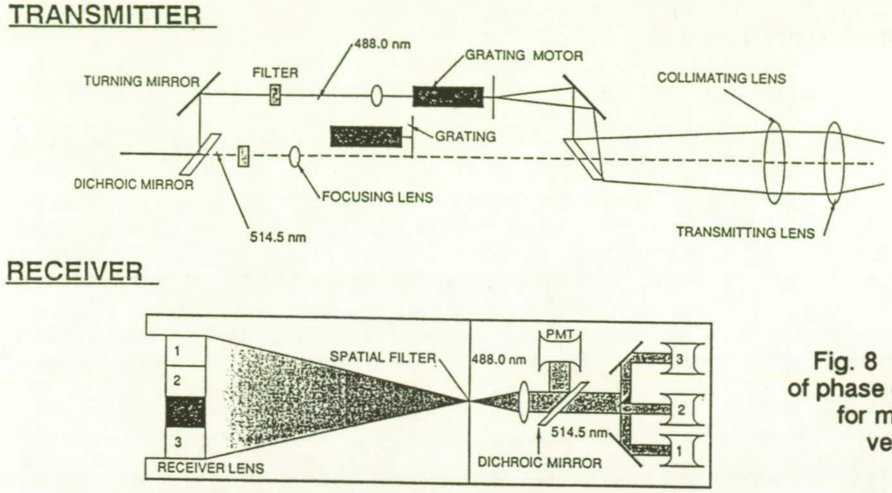
Another measurement needed is that of radiative flux (spectrally and directionally resolved) at the combustion chamber wall. This information is needed for comparison with predictions of the flowfield model for code validation.

Types of Measurements Possible. Since the properties needed are radiative properties the measurements which are available for determining these properties are inherently optical measurements, including:

- emission measurements
- transmission (or extinction) measurements
- scattering measurements

The widest diversity occurs in the category of scattering measurements. Some of the promising techniques recently developed which were mentioned include phase doppler (for velocity and size distribution) as pictured in Fig. 8 and CARS (for, among other things, gas temperature). A technique being developed at Aerometrics called rainbow angle detection (for droplet temperature, velocity and size) was also mentioned.

While the preceding list of properties and techniques enumerates the information which is needed and the types of measurements possible, it does not indicate specifically how to extract the information desired from the measurements which can be made. That is the role of a clever experimentalist. It is easy enough to say that spatially resolved volume fraction and size distribution information is needed but extracting that information from a limited number of measurements in an often noisy environment is a much more formidable challenge indeed.


TRANSMITTER

RECEIVER

Fig. 8 Schematic diagram of phase doppler interferometer for measuring particle velocity and size

Finally, it was pointed out that there are really two purposes in making diagnostic measurements. One is to obtain physical insight. As more physical insight is gained, assumptions and models used in numerical simulation can be improved. The other purpose is to establish a data base. In the latter context it is imperative to have good experimental documentation. It was suggested that a standard data format would be helpful in this regard.

SUMMARY

To one degree or another, all of the objectives of this workshop were accomplished. There is obviously much more that could be said about specific diagnostic techniques and there has possibly been more progress made in the area of incorporation of radiation into CFD codes than was discussed at the workshop. Nevertheless, it appears that there is sufficient cause for giving closer attention to the influence of radiative transfer on the flow characteristics of combustion chambers. Such an effort will clearly result in a substantial impact in the areas of hardware design, reliability, and performance. There is also the potential for a significant improvement in the understanding and control of combustion instability.

There is also a need to begin to establish a data base for making radiation calculations in rocket combustion chambers. A natural starting point for this effort would be the NASA thermochemical equilibrium code (CEC). Currently the CEC code calculates all the necessary thermodynamic properties (enthalpy, specific heat, density, entropy, etc.) but only a limited set of transport properties (thermal conductivity, viscosity, and diffusion coefficient). The CEC code needs to be extended to be able to calculate radiative properties (such as absorption coefficient, scattering coefficient, etc.) for rocket combustion chamber gas mixture compositions.

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