JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 19, No. 3, July–September 2005

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Aircraft Plume Infrared Signature in Nonafterburning Mode

S. P. Mahulikar,* G. A. Rao,† S. K. Sane,‡ and A. G. Marathe‡
Indian Institute of Technology Bombay, Mumbai 400 076, India

Nomenclature

dS	=	mean thickness of differential volume element of plume (parallel to emission), m
dV	=	differential volume element of plume, m^3
$e_{b\lambda}$	=	spectral emissive power of blackbody (given by Planck's law), W/m$^2\cdot\mu$m
I_λ	=	spectral radiant intensity, W/m$^2\cdot$Sr$\cdot\mu$m
P	=	pressure, Pa
T	=	temperature, K
α_λ	=	spectral gas absorptivity coefficient, μm^{-1}
β_λ	=	spectral gas extinction coefficient, μm^{-1}
λ	=	wavelength, μm
$\sigma_{S\lambda}$	=	spectral gas scattering coefficient, m^{-1}

Introduction

INFRARED (IR) signature is an effective passive technique of detecting and locking on to an aircraft; hence, predicting aircraft IR signature is an important aspect of aircraft susceptibility assessment. An integrated overview of stealth technology and the growing relative importance of IR signatures are discussed by Rao and Mahulikar.[1]

Background and Motivation

Plume IR signature modeling is of direct interest for assessing susceptibility to IR guided missiles. A brief methodology for computing plume IR signature from a naval gas turbine is given by Bakker et al.[2] They used NATO's plume flowfield program NPLUME for computing ship exhaust plume flowfields. The naval ship IR signature countermeasure and threat engagement simulator by Vaitekunas et al.[3] describes IR signature modeling from various sources in a naval ship (including plume radiation). Rapanotti et al.[4] described plume IR emission modeling for missiles. A model to evaluate IR emission from turbofans for designing engine exhaust nozzle is described by Decher.[5] The model uses empirical correlations for modeling the physical flowfield of the plume. The spectral emissivity characteristics of exhaust gases, transmissivity of atmosphere, missile characteristics, etc., were not considered. There is limited information reported on aircraft plume modeling with the objective of assessing its IR signature in the nonafterburning mode. Aircraft plume has been considered a major source of IR signature, especially in early generation fighter aircraft with turbojet engines and in the afterburner mode. With the advent of long-wavelength band IR detectors, the emphasis shifted from the plume to other sources. There still exists a popular belief that plume is invariably the dominant source of IR signature.

Objective and Scope

This Note describes a methodology to evaluate IR radiation emitted by plume and received by a ground-based IR detector (after attenuation by the intervening atmosphere) and compares plume IR signature with other sources such as rear fuselage and tailpipe. The objective is to reexamine the notion regarding the significance of plume IR radiation in the nonafterburning mode.

Aircraft Plume Modeling

The high-temperature plume ejected from nozzle is a mixture of several species in gaseous state (solid and liquid phases being generally negligible) that are produced from the combustion of hydrocarbon fuel. Gases with asymmetrical molecular structures such as H_2O, CO_2, and CO are responsible for the emission of IR radiation from the plume. Other species in the plume such as O_2, N_2, Ar, etc., are radiatively inert up to very high temperatures and do not emit significantly, even in the afterburning mode.[6] IR radiation from gases in the plume is emitted due to their vibrational energy. These gases emit radiation only in the IR range of the electromagnetic spectrum. Unlike metals and most solids, the emissivity of gas changes sharply with wavelength. Hence, plume emits only in a few discrete bands of the IR spectrum. However, the plume length is several times more than the aircraft length; consequently, plume radiation is visible from much wider view angles as compared to the engine tailpipe (visible only in the rear aspect).

Gas Radiation Modeling

The energy needed to induce transitions in vibrational levels of molecules is higher than rotational. Often, vibrational transitions are overlapped with rotational transitions, resulting in vibration–rotation bands. Molecular gases absorb and emit radiation over several vibration–rotation bands, which consist of several narrow spectral lines that may overlap (partially or fully) with one another.[7] The emissivity of a gas volume is a function of temperature, pressure, molar concentration of the radiative participating species and of the optical path length. Treating combustion gases as gray/semigray results in substantial errors in spectral radiative heat fluxes.[8] Radiative heat transfer calculations in combustion gases can be grouped into three methods: line-by-line, narrow band, and global[9]; the most accurate is the line-by-line approach.[10,11] However, this method needs a huge database to cover the entire IR spectrum for typical combustion gases, which is impractical to apply to engineering problems. Recently, the elaborate wavelet expansion method has been used to evaluate spectral dependence in the solution of the radiative transfer equation, and nongray radiation through absorbing, emitting, and nonscattering medium between parallel plates has also been analyzed.[12]

Received 20 November 2004; revision received 1 February 2005; accepted for publication 5 February 2005.

*Faculty Member, A. von Humboldt Fellow, Department of Aerospace Engineering; spm@aero.ittb.ac.in.
†Research Scholar, Department of Aerospace Engineering. Student Member AIAA.
‡Faculty Member, Department of Aerospace Engineering.

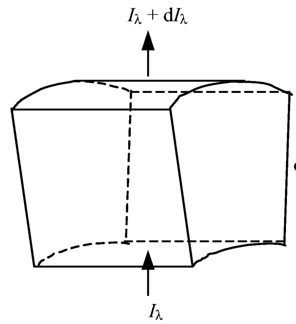

Fig. 1 Differential element of axisymmetric plume.

When spectral radiative heat fluxes are calculated from gases, it is noted that the gas absorption coefficient varies rapidly across the spectrum. Hence, the actual absorption coefficient is replaced by smoothened values, appropriately averaged over a narrow spectral band. A comprehensive method for obtaining emission from gases of hydrocarbon combustion using the statistical narrowband model is given by Soufiani and Taine.[13] It was shown earlier[14] that the most accurate statistical model for species generated from the combustion of hydrocarbon fuels is the random model with the S^{-1} exponential-tailed distribution of line intensities suggested by Malkmus[15] that also considers the several weak lines that arise in the bands, especially at high temperatures.

Plume IR Signature Prediction

For predicting IR emission from plume, its structure, that is, temperature, pressure, species distribution, and radiation transfer, must be simultaneously computed. To simplify this process, the plume structure is computed separately using a standard commercial computational fluid dynamics (CFD) solver. The plume is generated for a typical single-engine fighter aircraft (with axisymmetric nozzle), at 5-km altitude and Mach number 0.8. The plume IR solver reads the temperature and pressure profile as computed by the CFD solver. The planar grid is revolved to generate a three-dimensional axisymmetric plume, which is further discretized circumferentially to create isothermal gas volumes (Fig. 1). Plume IR signature is maximum when the aircraft is directly above the missile site, and only IR radiation emitted by the plume in the radial direction is visible to the detector. For a missile on the ground, the rear end of the plume is visible only from the aircraft rear view, and the plume acts more as an absorber of tailpipe emission than a radiation source (because the plume is at lower temperature and has lower emissivity as compared to the tailpipe). Therefore, only radiation heat transfer in the radial direction of the plume is considered here. The radiation heat transfer between various isothermal discretized volumes of the plume is computed. Furthermore, plume IR radiation in the dry mode of an engine is considered (in which unburnt hydrocarbon and soot are negligible).

For an isotropic absorbing and emitting elemental volume of gas, the spontaneously emitted intensity of radiation in any direction is given by[16] $dI_\lambda(\lambda, T) = [\alpha_\lambda(\lambda, T, P) \cdot e_{b\lambda}(\lambda, T) \cdot dS]/\pi$. A beam with radiation intensity I_λ that passes through a slab of gas undergoes a change in its intensity by an amount dI_λ, which is a result of the following effects:

1) The I_λ is augmented by emission from the elemental volume by

$$dI_\lambda = [\alpha_\lambda(\lambda, T, P) \cdot e_{b\lambda}(\lambda, T) \cdot dS]/\pi \tag{1}$$

2) Absorption by gases attenuate I_λ as it passes through dV, which is evaluated as $dI_\lambda = \beta_\lambda(\lambda, T, P) \cdot I_\lambda(\lambda, T) \cdot dS$, where $\beta_\lambda = \alpha_\lambda + \sigma_{S,\lambda}$. When scattering is assumed to be negligible, $\beta_\lambda = \alpha_\lambda$, and this equation is written as

$$dI_\lambda = \alpha_\lambda(\lambda, T, P) \cdot I_\lambda(\lambda, T) \cdot dS \tag{2}$$

When Eqs. (1) and (2) are combined, the net change undergone by I_λ in passing through the discretized gas volume is given as $dI_\lambda = \alpha_\lambda(\lambda, T, P) \cdot dS \cdot \{[e_{b\lambda}(\lambda, T)/\pi] - I_\lambda\}$. The monochromatic absorptivity coefficient of discretized isothermal gas volume α_λ is computed using the statistical narrowband model described by Soufiani and Taine[13] and using the data by Modest and Zhang.[9] The concentration of radiation participating gases is obtained by assuming the Schmidt number as unity, which holds for most gases and their mixtures; consequently, isothermal zones are the same as isoconcentration zones.

Results and Discussion

The aircraft lock-on range is a function of the IR detector's noise equivalent irradiance[17] and the contrast generated by the target aircraft with respect to the background radiance.[18] For estimating the IR signature level incident on the detector, the plume is assumed as optically thin; hence, spectral correlation phenomenon and the consequent self-absorption are not considered, thereby overestimating plume IR signature level. The role of the atmosphere in dictating IR signature levels produced by the rear fuselage and engine tailpipe and a methodology of computing the background radiation have been discussed.[18–20] The methodology for computing IR signature from the plume of a typical fighter aircraft, as perceived by a ground-based IR detector on a surface-to-air missile (SAM), is shown in Fig. 2. The aircraft is considered to be cruising at zenith over the SAM site. Figure 3 shows the average I_λ of the discretized plume, which illustrates its prominence only in a few bands of the IR spectrum, the primary being the 4.15–4.45 μm band (due to

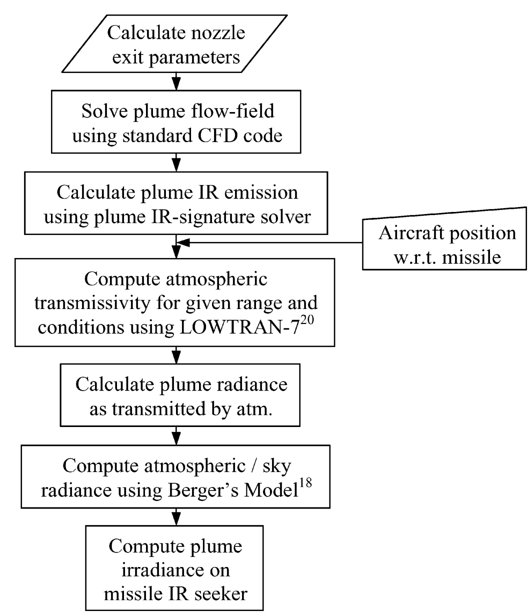

Fig. 2 Procedure for evaluating plume IR signature.

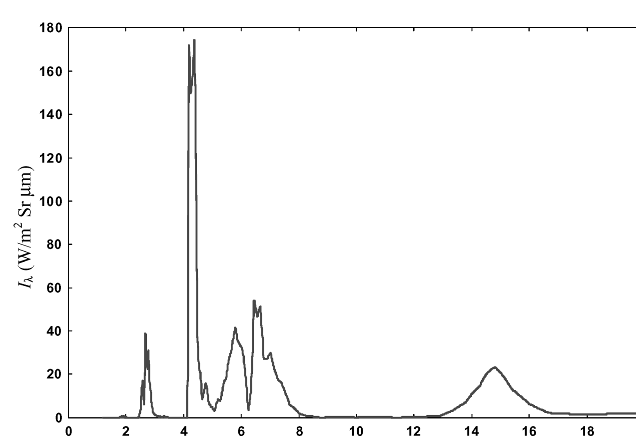

Fig. 3 Plume I_λ without atmospheric attenuation.

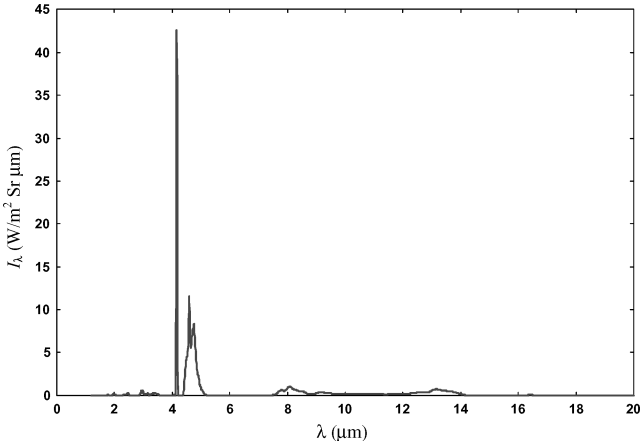

Fig. 4 Plume I_λ considering atmospheric attenuation.

the fundamental vibrational frequency of CO_2 and CO). However, most bands in which plume radiation is significant coincide with atmospheric absorption bands[18] because the plume and the atmosphere have the same radiative participating species, but differ in temperature, mole fraction, and pressure. Hence, most IR radiation emitted by plume is absorbed by the intervening atmosphere. Primarily, the radiation emitted by the broadened wings of these emissive bands (due to higher temperature and species concentration of radiative participating gases in the plume) is transmitted by the atmosphere and reaches the IR detector of a SAM. This may not be the case for an air-to-air missile (AAM) fired from aircraft because atmospheric transmissivity at higher altitude is greater, hence, some of the emissive bands absorbed by the atmosphere in case of a SAM, are transmitted in case of an AAM. Hence, an AAM can lock onto its target aircraft from a longer distance than a SAM.

Figure 4 shows the I_λ of a plume, after transmission by the atmosphere; as illustrated, the plume is prominent only in the 4.15–4.20 μm band. The experimentally obtained spectral intensity of the plume of a passenger aircraft (Boeing 707) (Ref. 21) qualitatively matches with that shown in Fig. 4. The aircraft operating conditions, chemical composition of exhaust gases, atmospheric conditions, etc., are uncertain; hence, there is some quantitative discrepancy. Unlike the case of radiation from the rear fuselage and tailpipe, the plume does not emit any radiation in the 8–12 μm band. Hence, plume radiation is unaffected by the background radiation (dominant in the 5–25 μm range). The plume is transparent to radiation of a higher wavelength; hence, longwave IR radiation from the sky above is transmitted by the plume without significant attenuation. When IR signature level due to rear fuselage and engine tailpipe[18] is compared with the plume, it is seen that that the IR signature from tailpipe and rear fuselage is more prominent than the plume in the nonafterburning mode. The IR signature level due to the powerplant is prominent in the following bands: 1.95–2.50, 2.92–3.20, 3.24–4.18, 4.50–4.93, and 8.20–11.80 μm. Thus, in the nonafterburning mode, the aircraft is more susceptible due to IR radiation emitted by the powerplant than from the plume.

Conclusions

1) The spectral intensity of aircraft plume as received by an IR-guided SAM in nonafterburning mode is prominent only in the 4.15–4.20 μm band.

2) Most plume IR radiation is absorbed by the intervening atmosphere; primarily, it is the radiation emitted from the broadened wings of the plume emissive bands that reaches the detector.

3) The background radiation does not significantly affect the plume IR signature level.

4) In the nonafterburning mode, the IR signature from plume is much lower than from tailpipe and rear fuselage; especially with the use of 8–12 μm band IR detectors.

Acknowledgments

The authors thank the Aeronautics Research and Development Board (Propulsion Panel), Government of India, for support. The authors are grateful to the A. von Humboldt Foundation, Germany, for the wealth of exposure to research. The authors thank the reviewers for the valuable suggestions for improving this Note and the Associate Editor for meticulous processing.

References

[1]Rao, G. A., and Mahulikar, S. P., "Integrated Review of Stealth Technology and Its Role in Airpower," *Aeronautical Journal*, Vol. 106, No. 1066, 2002, pp. 629–641.

[2]Bakker, E. J., Fair, M. L., and Schleijpen, H. M. A., "Modelling Multi Spectral Imagery Data with NIRATAM v3.1 and NPLUME v1.6," *Proceedings of SPIE Targets and Backgrounds: Characterization and Representation V Conference*, Vol. 3699, The International Society for Optical Engineering, Bellingham, WA, 1999, pp. 80–91.

[3]Vaitekunas, D. A., Alexan, K., Lawrence, O. E., and Reid, F., "SHIPIR/NTCS: A Naval Ship Infrared Signature Countermeasure and Threat Engagement Simulator," *Proceedings of SPIE Infrared Technology and Applications XXII*, Vol. 2744, The International Society for Optical Engineering, Bellingham, WA, 1996, pp. 411–424.

[4]Rapanotti, J., Gilbert, B., Richer, G., and Stowe, R., "IR Sensor Design Insight from Missile-Plume Prediction Model," *Proceedings of SPIE Targets and Backgrounds VIII: Characterization and Representation*, Vol. 4718, The International Society for Optical Engineering, Bellingham, WA, 2002, pp. 289–300.

[5]Decher, R., "Infrared Emissions from Turbofans with High Aspect Ratio Nozzles," *Journal of Aircraft*, Vol. 18, No. 12, 1981, pp. 1025–1031.

[6]Lefebvre, A. H., "Heat Transfer," *Gas Turbine Combustion*, Hemisphere, Washington, DC, 1983, pp. 259–262.

[7]Sparrow, E. M., and Cess, R. D., "Thermal Radiation," *Radiation Heat Transfer*, Hemisphere, Washington, DC, 1978, pp. 2–20.

[8]Edwards, D. K., "Molecular Gas Band Radiation," *Advances in Heat Transfer*, edited by T. F. Irvine and J. P. Hartnett, Vol. 12, Academic Press, New York, 1976, pp. 115–193.

[9]Modest, M. F., and Zhang, H., "The Full Spectrum Correlated-k Distribution for Thermal Radiation from Molecular Gas-Particulate Mixtures," *Journal of Heat Transfer*, Vol. 124, No. 1, 2002, pp. 30–38.

[10]Hartmann, J. M., Levi Di Leon, R., and Taine, J., "Line-by-Line and Narrow-Band Statistical Model Calculations for H_2O," *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 32, No. 2, 1984, pp. 119–127.

[11]Rothman, L. S., Gamache, R. R., Tipping, R. H., Rinsland, C. P., Smith, M. A. H., Benner, D. C., Devi, V. M., Flaud, J. M., Peyret, C. C., Perrin, A., Goldman, A., Massie, S. T., Brown, L. R., and Toth, R. A., "The Hitran Molecular Database Editions of 1991 and 1992," *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 48, No. 516, 1992, pp. 469–507.

[12]Wang, Y., and Bayazitoglu, Y., "Wavelets and Discrete Ordinates Method in Solving One-Dimensional Nongray Radiation Problem," *International Journal of Heat and Mass Transfer*, Vol. 42, No. 3, 1999, pp. 385–393.

[13]Soufiani, A., and Taine, J., "High Temperature Gas Radiative Property Parameters of Statistical Narrow-Band Model for H_2O, CO_2 and CO, and Correlated-K Model for H_2O and CO_2," *International Journal of Heat and Mass Transfer*, Vol. 40, No. 4, 1997, pp. 987–991.

[14]Soufiani, A., Hartmann, J. M., and Taine, J., "Validity of Band-Model Calculations for CO_2 and H_2O Applied to Radiative Properties and Conductive-Radiative Transfer," *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 3, No. 3, 1985, pp. 243–257.

[15]Malkmus, W., "Random Band Lorentz with Exponential Tailed S^{-1} Line-Intensity Distribution Function," *Journal of the Optical Society of America*, Vol. 57, No. 3, 1967, pp. 323–329.

[16]Siegel, R., and Howell, J. R., "The Equations of Energy Transfer for Absorbing, Emitting, and Scattering Media," *Thermal Radiation Heat Transfer*, Hemisphere, Washington, DC, 1981, pp. 450–461.

[17]Hudson, R. D., "Introduction to Detectors," *Infrared System Engineering*, Wiley-Interscience, New York, 1969, pp. 264–271.

[18]Rao, G. A., and Mahulikar, S. P., "Effect of Atmospheric Transmission and Radiance on Aircraft Infrared Signatures," *Journal of Aircraft* (to be published).

[19]Kneizys, F. X., Shettle, E. P., Gallery, W. O., Chetwynd, J. H., Abreu, L. W., Selby, J. E. A., Clough, S. A., and Fenn, R. W., "Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 6," U.S. Air Force Geophysics Lab., Rept. AFGL-TR-83-0187, Hanscom AFB, MA, 1983.

[20]Lowtran 7 Computer Code: User's Manual, U.S. Airforce Geophysics Lab., Rept. AFGL-TR-88-0177, Hanscom AFB, MA, 1988.

[21]La Rocca, A. J., "Artificial Sources," *The Infrared Handbook*, edited by W. L. Wolfe and G. J. Zissis, Office of Naval Research, Washington, DC, 1985, pp. 2.76–2.82.