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Assessment of Turbulence–Chemistry Interactions in Missile Exhaust Plume Signature Analysis

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Introduction

THE evolution of missile exhaust plume signatures plays a significant role in the radiative heat transfer to missile base components and in the development of missile defense systems. However, accurate prediction of missile plume signatures is a difficult problem, especially over the altitude range where plume afterburning becomes quenched or shuts downs. Plume afterburning shutdown in this context does not refer to the termination of the missile engine, but to the cessation of the combustion taking place between the missile exhaust and the atmosphere, occurring with continuous engine operation. Signature prediction methodologies, including engineering-level models (e.g., Ref. 1), typically underpredict afterburning plume temperatures and emissions near the afterburning shutdown altitude regime and do not accurately capture the quenching process.

In an effort to improve understanding into the physical mechanisms involved with missile plume afterburning and afterburning shutdown, Calhoon[2] investigated the shutdown characteristics of a generic amine booster system within the framework of a computational parametric study. One conclusion from that study was that turbulence–chemistry interactions play a significant role in the quenching process involved with afterburning shutdown.

For high speed flows turbulence–chemistry interactions have been shown to enhance burning for flames near the ignition limit.[3] To include this effect within high-speed flow simulations, two comprehensive turbulence–chemistry interaction models are available. These two models are the assumed probability density function (PDF) method[4] and the compressible extension of the PDF evolution equation method.[5,6] Though providing a more accurate description of the higher-order statistics of the turbulent scalar fields, the PDF evolution equation method has not been shown to yield significantly better results than the assumed PDF method when applied to compressible flows. The PDF evolution equation method is also computationally expensive and can become intractable when applied to flows including shock waves.[6] The assumed PDF method, on the other hand, is computationally inexpensive and offers a viable approach to account for turbulence–chemistry interactions in complex, large-scale flows of practical interest.

The objective of this study was to assess the impact of turbulence–chemistry interactions on the afterburning and afterburning shutdown characteristics of the generic missile system investigated by Calhoon.[2] This assessment was carried out using the assumed PDF method of Gaffney et al.,[4] described in detail by Calhoon and Kenzakowski.[7] This model has been implemented within the CRAFT CFD[8] fluid flow solver used to perform the missile plume simulations in this study.

The following section presents results for the prediction of afterburning shutdown for the generic missile configuration of Calhoon.[2] These results indicate that turbulence–chemistry interactions do play a significant role in the afterburning and afterburning shutdown characteristics of this missile system.

Results and Discussion

The simulations considered in this study were carried out for the generic axisymmetric amine booster described in detail by Calhoon.[2] Problem setup and boundary conditions for these simulations are also described in detail by Calhoon and Kenzakowski.[7] The missile plume flowfield simulations were calculated at three altitudes (25, 30, and 35 km) both with and without the use of the PDF turbulence–chemistry interaction model. These altitudes were selected because they span the afterburning shutdown regime for this generic booster, given an assumed trajectory profile.[2] The Reynolds and Mach numbers based on freestream conditions and the body radius were $Re_\infty = 4 \times 10^6$, 2×10^6, and 1×10^6 and $M_\infty = 2.6$, 3.2, and 3.9 for the altitudes of 25, 30 and 35 km, respectively.

As described by Calhoon,[2] the altitude conditions of 25, 30, and 35 km characterize the afterburning shutdown regime of the present generic booster system when the simulations neglect the effect of turbulence–chemistry interactions. Under this circumstance the plume at 25 km is burning vigorously, whereas at 30 km it has progressed deeply into the shutdown regime. At 35 km the plume flame is almost completely extinguished.

Application of the PDF model to these flight conditions was found to have a substantial impact on the afterburning characteristics of this system. The model enhanced the combustion characteristics within the flow so that the plume flame at each altitude ignited substantially closer to the missile base than for the cases when turbulence–chemistry interactions were neglected. Consequently, when the PDF model was included, the plumes afterburned more vigorously than when it was neglected. To illustrate this point, Fig. 1 presents a plot of CO_2 mole fraction across the plume at a fixed downstream location of $x/x_{\rm refl} = 3$ for the 35-km case. The length scale $x_{\rm refl}$ is the distance between the nozzle exit plane and the barrel shock reflection point at the axis of symmetry. The transverse coordinate in this figure has also been scaled by δ which is the location where the N_2 mole fraction is 99% of its freestream value. From this figure the PDF model is seen to substantially enhance the formation of CO_2 at this downstream location. When turbulence–chemistry interactions were neglected, plume ignition occurred much further downstream so that plume afterburning was nearly quenched.

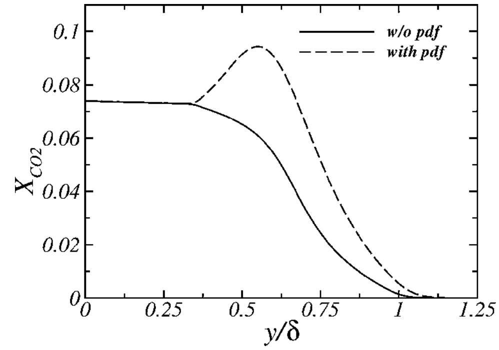

Fig. 1 Prediction of transverse mean CO_2 mole fraction at $x/x_{\rm refl} = 3$ for the 35-km case, both with and without using the PDF model.

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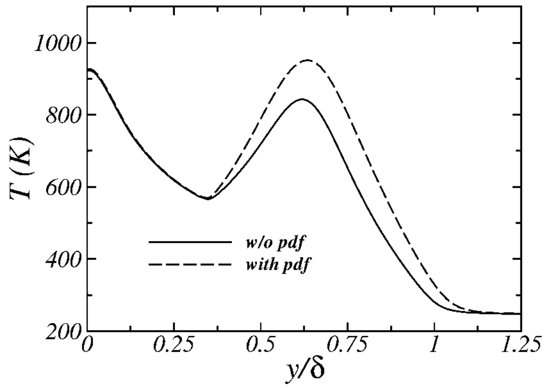

Fig. 2 Prediction of transverse mean temperature at $x/x_{\mathrm{refl}} = 3$ for the 35-km case, both with and without using the PDF model.

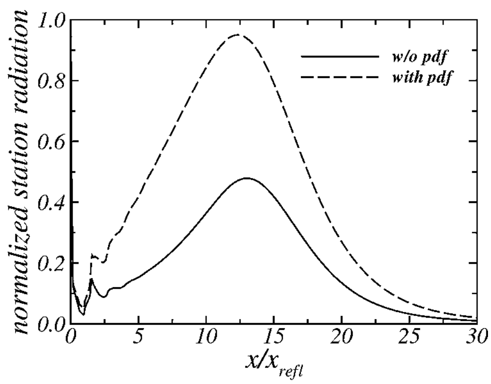

Fig. 3 Source station radiation for the 35-km case, both with and without using the PDF model.

The enhanced product formation seen in Fig. 1 results in substantially higher plume temperatures as seen in Fig. 2. This figure presents temperature plots again at $x/x_{\mathrm{refl}} = 3$ for the 35-km case, both with and without inclusion of the PDF model. The case including turbulence–chemistry interactions is seen to obtain a peak shear-layer temperature of more than 100 K higher than when this effect is neglected. This enhanced combustion for the PDF model case at 35 km was also observed for the other altitude conditions.

Gaffney et al.[3] found temperature fluctuations resulting from turbulent mixing to enhance chemical reactions and ignition for high-speed H_2–air shear-layer flames that were far from equilibrium. The same observation can be made here with regard to CO/H_2-air combustion occurring in these amine missile plume flames. For the present plume application, when turbulence–chemistry interactions were neglected, the plume flames were far from equilibrium and on the edge of burnout. When the PDF model was included, temperature fluctuations enhanced product formation, resulting in higher plume temperatures and a delay in afterburning shutdown.

The large increase in plume temperatures for the PDF model simulations correspondingly resulted in a large increase in plume radiative emissions. Figures 3 and 4 present comparisons of station radiation and total radiant intensity, respectively. These radiation calculations were carried out as described by Calhoon and Kenzakowski[7] using a wide bandpass to encompass emissions from OH, CO, CO_2, and H_2O. The total radiation intensity predictions were also made using a field of view large enough to encompass the entire plume. From Fig. 3 the station radiation at 35 km is seen to be significantly larger when the PDF model is included, resulting from the enhanced burning for that case. The higher station radiation predictions in Fig. 3 produce significant differences in the total plume intensity as seen in Fig. 4. This figure presents results for all simulated altitude conditions. As seen in Fig. 4, the PDF model produces high total intensity for all simulated altitudes. However, note that the PDF model has a greater influence as altitude is increased.

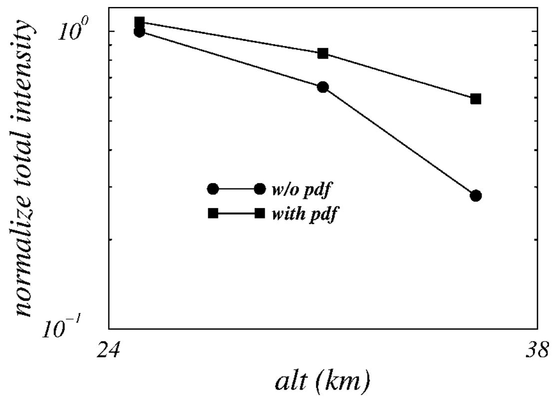

Fig. 4 Comparison of model predictions of source total radiant intensity as a function of altitude at a 90-deg aspect angle.

This results from the fact that the model delayed the onset of plume afterburning shutdown. The PDF model also significantly slowed the rate of decay of total intensity as afterburning was quenched.

Conclusions

A computational study was undertaken to assess the impact of turbulence–chemistry interactions on the afterburning and afterburning shutdown characteristics of a generic amine booster. Turbulence–chemistry interactions were accounted for using an assumed PDF-based method. Analysis of the simulation results found turbulence–chemistry interactions modeled using the PDF method to have a first-order effect and to have a large impact on plume signatures as afterburning shutdown was approached. The PDF model was found to enhance plume afterburning and delay the onset of shutdown causing the plume to burn to higher altitudes than when the model was not included.

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