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Technical Comments

Brief discussion of previous investigations in the aerospace sciences and technical comments on papers published in the Journal of Spacecraft and Rockets *are presented in this special department. Entries must be restricted to a maximum of 1000 words, or the equivalent of one* Journal *page including formulas and figures. A discussion will be published as quickly as possible after receipt of the manuscript. Neither the AIAA nor its editors are responsible for the opinions expressed by the correspondents. Authors will be invited to reply promptly.*

Comment on "X-33 Computational Aeroheating Predictions and Comparisons with Experimental Data"

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THE recent paper of Hollis et al.[1] omits a key reference to our work[2] on the X-33 program (Phase II). Further, crucial results from the paper[3] that *was* referenced are not discussed. These omissions diminish the research findings reported in Refs. 2 and 3 and lead to the erroneous inference that the X-33 aerothermal design environments are overly conservative.

The contentious paragraph of Ref. 1 (p. 261) is quoted here:

> The VLVLRo method was used for all subsequent computations, and its accuracy will be demonstrated in a later section where heating predictions generated using the VLVLRo method are compared with experimental data. In contrast, the much more dissipative VLVLVL scheme was employed in Ref. 27 to generate a design aeroheating database for the X-33 vehicle, which illustrates the need for independent verification of critical vehicle design data either through code-to-code comparisons, code-to-experiment comparisons, or both.

Reference 27 quoted in the preceding paragraph is the same as Ref. 3 listed here. Letting VL denote Van Leer flux-vector splitting and Ro denote Roe flux-difference splitting, VLVLRo and VLVLVL stand for the inviscid flux formulation in the three coordinate directions with the third direction taken as normal to the body surface. The quoted paragraph states that the present authors' choice of VLVLVL scheme for the inviscid fluxes is "much more dissipative" than VLVLRo, implying that the resulting X-33 environments are overly conservative.

To discuss this claim, we preface our comments with a brief background on the process involved in arriving at the design aerothermal environments for the X-33 flight vehicle. The aerothermal environments team comprised of researchers and engineers from Lockheed Martin, NASA Ames and Langley Research Centers, and NASA Marshall Space Flight Center. NASA Ames Research Center provided computational fluid dynamic predictions of the acreage environments required for the design of the thermal protection system. The process for computing these environments is outlined in the work of Prabhu et al.,[2] rather than in Ref. 3 as stated by Hollis et al. Although the process described therein is for the D and Rev C configurations, the same process was followed for the final configuration, Rev F. The work described in Ref. 3 was focused on verification/validation of the computational tools through comparison of numerical results against data from wind-tunnel experiments performed as part of the X-33 program at NASA Langley Research Center.[4]

Central to the process of numerical prediction of acreage environments is Version 3 of the commercially available code GASP,[5] which was used with in-house modifications for computing the X-33 aerothermal environments. Of the several available choices for numerical and thermophysical models, Van Leer flux-vector splitting for the inviscid fluxes and a five-species chemical nonequilibrium air model were used in all computations.[2] As stated in Ref. 3, this choice of models (both numerical and physical) was largely guided by experience with Version 2 of GASP used during Phase I of the X-33 program. In Phase II, Version 3 of GASP was used because of its improved efficiency and robustness and additional thermophysical modeling capabilities. Because the two versions of GASP are substantially different, testing, which was limited by program schedule, was performed on simple configurations with very refined grids to ensure the results of the two versions were the same. The key point here is that the testing was done on extremely fine grids, which gave results that were very close to each other, independent of the choice of inviscid flux formulation.

We are quite aware that the numerical dissipation introduced by the Van Leer inviscid flux formulation is larger than that of the Roe scheme. However, the grid refinement study in Ref. 3 shows that the increased dissipation of the Van Leer scheme can be reduced through the use of fine grids. The work in Ref. 3 also shows that, in an attempt to reconcile the initial differences between computation and experiment,[5] the excessive numerical dissipation (even beyond that of the original Van Leer scheme) was traced to the implementation of the min-mod limiter in Version 3 of GASP, which was modified from Version 2. In particular, the problem was traced to the compression parameter ϕ, which is defined as

$$\phi = (3 - \kappa)/(1 - \kappa) \tag{1}$$

where $\kappa = \frac{1}{3}$ for nominal third-order accuracy. The released Version 3 of GASP had ϕ "hard wired" to unity independent of the input value of κ, which made the Van Leer scheme even more dissipative.

The work of Hollis et al. does not mention three key conclusions that were made in Ref. 3:

1) For laminar flow the VLVLVL scheme on fine grids with $\phi = 1$ produces similar results to VLVLRo on the nominal grid.

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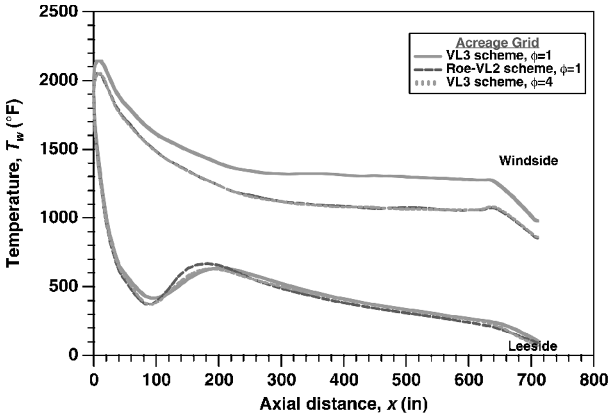

Fig. 1 Impact of ϕ parameter in the min-mod limiter on centerline radiative equilibrium temperatures for the X-33 Rev F configuration at peak laminar heating point ($M_\infty = 11.436$, $\alpha = 35.8$ deg, $Re_\infty = 46.232 \times 10^3$/ft) on the design trajectory. VL3 is VLVLVL and Roe-VL2 is VLVLRo.

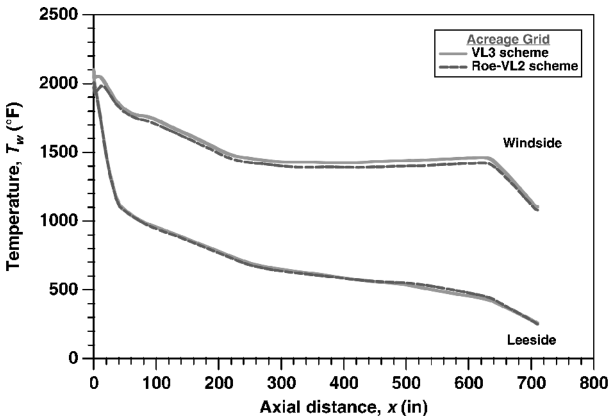

Fig. 2 Impact of inviscid flux formulation (with $\phi = 1$) on centerline radiative equilibrium temperatures for the X-33 Rev F configuration at peak turbulent heating point ($M_\infty = 10$, $\alpha = 20$ deg, $Re_\infty = 63.916 \times 10^3$/ft) on the design trajectory. VL3 is VLVLVL and Roe-VL2 is VLVLRo.

2) For laminar flow the VLVLVL scheme with $\kappa = \frac{1}{3}$ in Eq. (1) produces similar results to VLVLRo. There are no additional grid requirements. This is shown in Fig. 1 (reproduced from Ref. 3) for the peak laminar heating point of the design trajectory.

3) For turbulent flow the VLVLVL and VLVLRo schemes produce similar results independent of the min-mod formulation because the turbulent viscosity is much larger than the numerical dissipation. This result is shown in Fig. 2 (reproduced from Ref. 3) for the peak turbulent heating point on the design trajectory. This result is particularly important because the candidate flight trajectories were dominated by turbulent flow conditions. Further, the splitlines for the thermal protection system were determined by the predicted aerothermal environment at the peak turbulent heating point on the design trajectory.[2] Therefore, an overprediction of the laminar flight environments would have little impact on the overall conservatism of the design of the thermal protection system.

In summary, the proper reference for describing the process for determining the X-33 design environments is Ref. 2. Furthermore, we clearly show in Ref. 3 that for laminar flow the VLVLVL scheme is no more dissipative than the VLVLRo scheme, provided the proper definition of the compression parameter ϕ [Eq. (1)] is used in the min-mod limiter. For turbulent flow, which was the primary driver for the X-33 TPS design, our choice of scheme, flux limiter, and grid does not lead to overly dissipative solutions as implied in the article of Hollis et al.[1] We wholeheartedly agree with the author's statement about the importance of validating numerical codes with reliable experimental data. In fact, such validation in the laminar regime is what allowed us to identify and trace the problem in the compression parameter definition, as described in Ref. 3.

Acknowledgments

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[1]Hollis, B. R., Horvath, T. J., Berry, S. A., Hamilton, H. H., II, Thompson, R. A., and Alter, S. J., "X-33 Computational Aeroheating Predictions and Comparisons with Experimental Data," *Journal of Spacecraft and Rockets*, Vol. 38, No. 5, 2001, pp. 658–669.

[2]Prabhu, D. K., Loomis, M. P., Venkatapathy, E., Polsky, S., Papadopoulos, P., Davies, C. B., and Henline, W. D., "X-33 Aerothermal Environment Simulations and Aerothermodynamic Design," AIAA Paper 98-0868, Jan. 1998.

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[4]Horvath, T. J., Berry, S. A., Hollis, B. R., Liechty, D. S, Hamilton, H. H., II, and Merski, N. R., "X-33 Experimental Aeroheating at Mach 6 Using Phosphor Thermography," *Journal of Spacecraft and Rockets*, Vol. 38, No. 5, 2001, pp. 634–645.

[5]"GASP Version 3 User's Manual," AeroSoft, Inc., Blacksburg, VA, 1996.

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Reply by the Author to Prabhu et al.

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IN their Comments Prabhu et al. raise three concerns with regard to the recently published paper "X-33 Aeroheating Predictions and Comparisons with Experimental Data."[1] In this response each of these concerns shall be dealt with individually.

1) The first concern is that the earlier work[2] of Prabhu et al. was neglected and only the more recent work[3] was discussed: "The recent article of Hollis et al. omits a key reference to our work on the X-33 program (Phase II)."

Inclusion of the earlier work of Prabhu et al. might have made the reference list more complete, but failure to do was hardly a critical flaw because the paper was neither explicitly or implicitly presented as an overview of the entire X-33 aeroheating program. As their most recent publication, which contains a thorough list of references to earlier work, was cited, there was obviously no intention to neglect the contributions of Prabhu et al.

2) The second concern is that the results of Ref. 3 of were not fully discussed: "...crucial results from the paper that was referenced are not discussed" (on the implementation of the min-mod limiter and its use with the VLVLVL flux formulation).

In response to this comment, compliments should first be offered to Prabhu et al. for discovering the problem with the formulation of the min-mod limiter (see Ref. 3 for details) in GASP Version 3.2.x. They should be encouraged to submit their work to this journal

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