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Toward High-Enthalpy Simulations for Hypersonic Applications: The Double Cone Test Case

by Vishal A Bhagwandin and Jubaraj Sahu

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14. ABSTRACT Computational modeling approaches for chemical and thermal nonequilibrium hypersonic flows were investigated. The test case was a canonical double-cone in a Mach 13, high-enthalpy 22 MJ/kg flow environment, modeled after the University of Queensland X3 wind tunnel experiments. State-of-the-art numerical simulations employed full Navier-Stokes with multi-specie finite-rate chemical kinetics, vibrational relaxation, coupling of vibration and dissociation via a two-temperature nonequilibrium approach, and modeling of viscosity, thermal conductivity and diffusion transport properties specifically geared for high-temperature gases. Flow-field solutions showed complex shock-shock and shock-boundary layer interactions. The high-temperature post-shock showed a high degree of dissociation of nitrogen and oxygen, vibrational excitation, and thermochemical nonequilibrium. Predicted surface pressures and peak heat flux matched well with experiment; however, uncertainties exist in the general prediction of heat flux and corner flow separation. Additionally, the use of a single-specie perfect gas model emphasized the need for modeling high-temperature gas effects. The perfect gas model retained more energy in the flow, which drastically changed the shock structures, and significantly overpredicted the extent of flow separation and peak heating.					
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Contents

List of Figures	iv
List of Tables	iv
Acknowledgments	v
1. Introduction	1
2. The Double-Cone Canonical Test Case and Current Modeling Capabilities	2
3. Navier-Stokes Simulations of the Double-Cone Configuration	5
3.1 Test Article and Wind Tunnel Flow Conditions	5
3.2 Computational Grids	6
3.3 Conservation Equations and Numerical Schemes	7
3.4 Physical Gas Models	8
3.5 Results	10
4. Conclusion	15
5. References	17
List of Symbols, Abbreviations, and Acronyms	19
Distribution List	20

List of Figures

Fig. 1	Relaxation behind normal shock.....	2
Fig. 2	Double-cone article.....	3
Fig. 3	Double-cone flow field, $h_{0,\infty} = 22$ MJ/kg and $M_\infty = 12.8$	4
Fig. 4	UQ X3 double-cone	5
Fig. 5	Grid level comparison.....	7
Fig. 6	Flow fields using TTNE model: streamwise velocity, temperature, and strain rate.....	11
Fig. 7	Flow fields using PG model: streamwise velocity, temperature, and strain rate.....	11
Fig. 8	Zoom of corner separation showing streamwise velocity: TTNE (left) and PG (right)	11
Fig. 9	Temperature fields using TTNE model: translational (left) and vibrational (right).....	13
Fig. 10	Species mass fractions using TTNE model (note contours scales are different)	13
Fig. 11	TTNE vs. PG: pressure, Stanton number, skin friction, and cell Reynolds number	14

List of Tables

Table 1	Wind tunnel flow conditions.....	6
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1. Introduction

There is increased interest in the development of hypersonic weapon systems for force projection to extended ranges with shorter flight times. The development of these systems presents many design challenges. At the hypersonic speeds of interest, typically above Mach 5, multiple complex flow phenomena emerge and can significantly impact system performance. In particular, the high-energy flow environment can cause certain thermodynamic processes to become important, commonly referred to as “real” gas effects. These processes incur significant changes in the flow field around the vehicle, including design parameters of interest such as aerodynamic pressures, forces, and moments and structural heating, ablation, and elasticity. These phenomena have a dominating impact on the aerothermal and aerodynamic performance of a hypersonic vehicle.

At lower speeds, such as in subsonic and supersonic flow, where the temperature rise is modest, fluid simulations often ignore real gas effects. Gases are typically modeled as thermally and calorically perfect. Perfect gases are assumed to be in thermodynamic equilibrium, that is, thermal, chemical, and vibrational equilibrium. Molecules are assumed to be rigid and intermolecular forces are neglected, and only translational energy constitutes the entire molecular energy. The gas then obeys the ideal equation of state as derived from kinetic theory or statistical mechanics. A calorically perfect gas is one in which the specific heat capacities are constant. A thermally perfect gas obeys the equation of state, but may or may not be calorically perfect. In a calorically imperfect gas, specific heats are a function of temperature because of vibrational and electronic excitation.

At hypersonic speeds, perfect gas assumptions break down as large amounts of kinetic energy are converted to heat energy surrounding the vehicle and the temperature rises beyond certain thresholds. In addition to translation, internal energy states—rotation, vibration, electronic—can be activated. Chemical reactions—dissociation, recombination, ionization—can occur. For example, for air consisting mainly of diatomic nitrogen and oxygen, above approximately 800 K vibrational excitation occurs where some of the energy of the gas transfers to intermolecular vibrational energy instead of raising the temperature of the gas. Above approximately 2500 K, oxygen molecules begin to dissociate, above approximately 4000 K, nitrogen molecules begin to dissociate, and above approximately 9000 K, electronic excitation occurs.¹ In gas modeling one may consider three thermochemical regimes: frozen, equilibrium, and nonequilibrium. In frozen flow, one assumes no changes in internal energy modes and no chemical reactions. In equilibrium flow, one assumes that energy transfer between modes and chemical reactions occurs such that the flow locally equilibrates infinitely fast.

Between the limits of frozen and equilibrium flow is nonequilibrium flow, where the time required to complete energy transfer between modes and chemical reactions is comparable to the characteristic flow time.

Typical hypersonic vehicles of interest are slender with a blunted nose. This design incurs an approximately normal shock near the nose and a strong oblique shock close to the vehicle's surface. At high enthalpies, the post-shock field is characterized by high heating and nonequilibrium thermochemistry. The shock layer can change significantly compared to perfect gas or equilibrium assumptions. The relaxation time and distance of quantities of interest past the shock becomes important. For example, Fig. 1 illustrates the relaxation of temperature behind a normal shock in nonequilibrium flow and the large differences between the frozen and equilibrium limits, particularly at higher speeds.² Thus, the entire flow field around the vehicle, and therefore the aerothermal and aerodynamic performance, is affected.

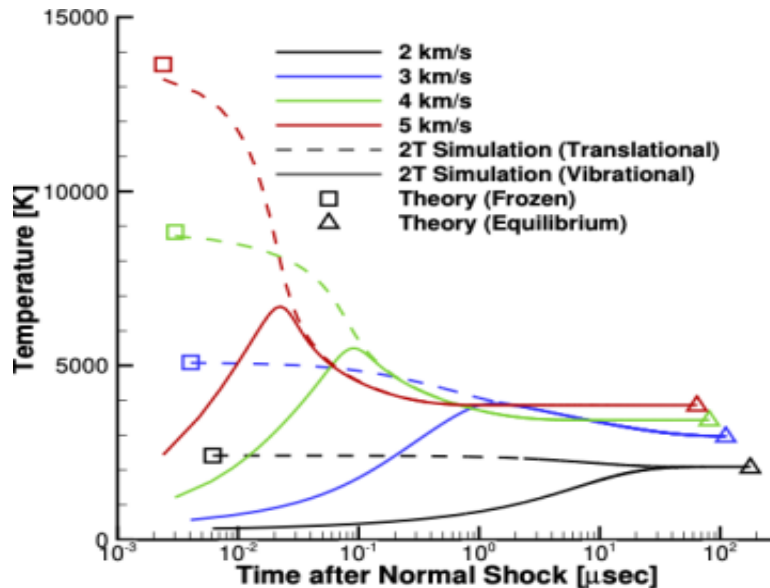


Fig. 1 Relaxation behind normal shock²

2. The Double-Cone Canonical Test Case and Current Modeling Capabilities

While there have been significant advances in computational fluid dynamics (CFD), there are still deficiencies in modeling real gas effects. A popular canonical test case is the double-cone configuration.³⁻⁵ The geometry, shown in Fig. 2, consists of a 25° cone followed by a 55° conical frustrum, with either sharp or blunted noses. The configuration is very sensitive to thermochemical modeling and presents excellent validation for numerical schemes and physical models used in

CFD. The flow is laminar so that real gas effects can be assessed without the interference of turbulence or transition. Experiments have been conducted on the double-cone in wind tunnels such as CUBRC LENS-XX,³ AEDC Tunnel 9,⁴ and the University of Queensland (UQ) X3⁵ tunnels. Freestream total enthalpies in the wind tunnels ranged from $h_0 = 5\text{--}22$ MJ/kg, with freestream velocities in the range 3–6.5 km/s, and Mach numbers in the range $M = 11\text{--}13$. The double-cone test case is characterized by two primary shock waves generated by each cone and a complex series of secondary shocks and flow structures at the juncture that result from shock–shock interactions (SSIs) and shock–boundary layer interactions (SBLIs), as illustrated in the plot in Fig. 3 generated by the simulations herein.

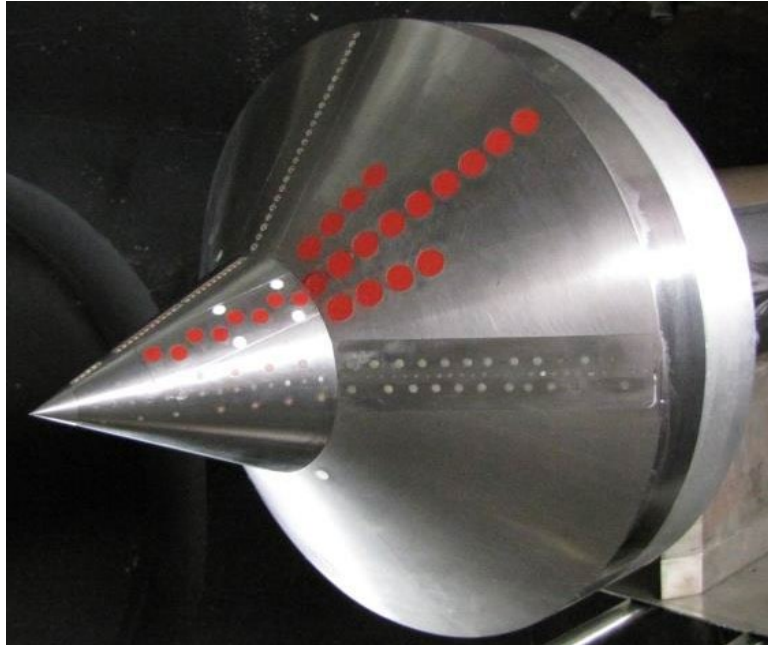


Fig. 2 Double-cone article⁶

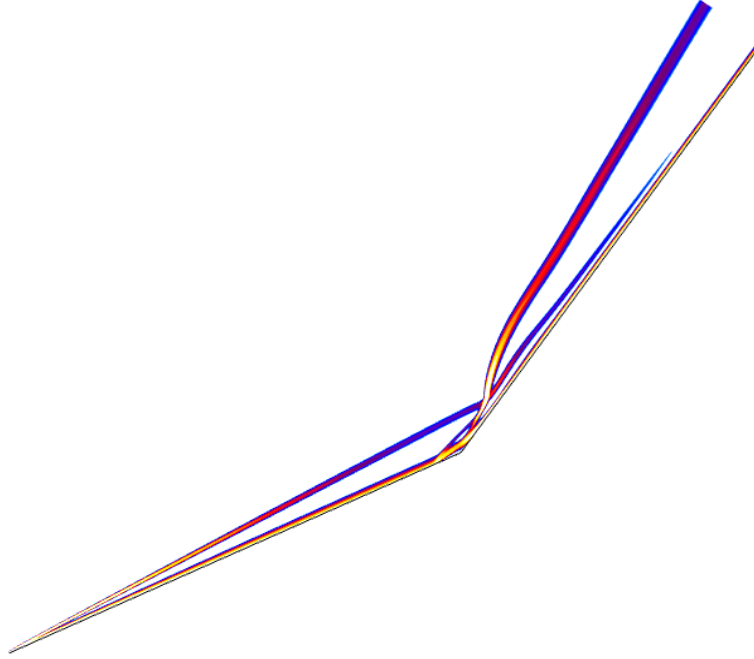


Fig. 3 Double-cone flow field, $h_{0,\infty} = 22$ MJ/kg and $M_\infty = 12.8$

At lower enthalpies, researchers have shown reasonable agreement between CFD and experiment.^{3,8-11} For example, at $h_{0,\infty} = 5.44$ MJ/kg and $M_\infty = 12.2$, Holloway et al.¹⁰ showed good to excellent agreement for wall surface pressure and heat transfer traces when using nonequilibrium models. However, at higher enthalpies, there are far more discrepancies between CFD and experiment.^{3,8-10} For example, at $h_{0,\infty} = 21.77$ MJ/kg and $M_\infty = 12.82$, Holloway et al.¹⁰ showed notable discrepancies in predicting the size and location of the separation event, and the extent and location of the peak pressure and heating, even with a nonequilibrium model.

Researchers have also used nitrogen only and oxygen only as the test gas in order to isolate the thermochemical mechanisms of each gas. For example, at $h_{0,\infty} = 9.65$ MJ/kg and $M_\infty = 10.9$, Holden et al.³ showed good agreement between CFD and experiment with nitrogen test gas, but there were notable discrepancies for oxygen and air ($N_2 + O_2$) test gases. This indicates that perhaps the modeling of thermochemical mechanisms associated with particular gases, such as oxygen, are deficient.

The aforementioned examples and references indicate that there are inaccuracies in modeling the thermochemistry as the total enthalpy, and therefore the degree of nonequilibrium, rises. There are a number of modeling factors to consider, such as the energy exchange models for vibration-translation, vibration-vibration, vibration-dissociation and vibration-electronic couplings, freestream

nonequilibrium, catalytic versus non-catalytic walls, slip versus no-slip walls, and transport models for viscosity, thermal conductivity, and diffusion. Additionally, CFD numerical convective flux schemes, time integration schemes, and computational grids can affect the accuracy of the results.

3. Navier-Stokes Simulations of the Double-Cone Configuration

3.1 Test Article and Wind Tunnel Flow Conditions

In this report, we explore a single high-enthalpy test case at $h_{0,\infty} = 22$ MJ/kg and $M_\infty = 12.8$ using Navier-Stokes modeling. This is the highest-enthalpy test case from the CUBRC LENS-XX and UQ X3 wind tunnel experiments, and likely the most stringent test case. The post-shock temperature is high such that it incurs significant dissociation of oxygen and nitrogen, vibrational excitation, and nonequilibrium. In this report, we present simulations of the X3 test case,⁵ which was intended to replicate the CUBRC test case.³ The X3 test article, shown in Fig. 4, is a scaled version of the CUBRC model. The CUBRC test results can still be compared using appropriate scalings. Table 1 shows the freestream conditions for both wind tunnels.

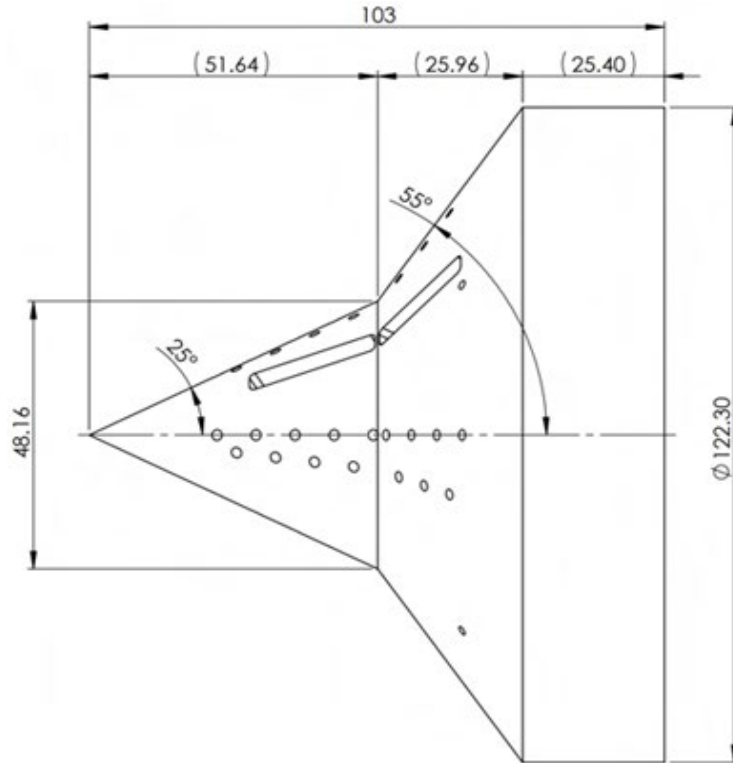


Fig. 4 UQ X3 double-cone⁵

Table 1 Wind tunnel flow conditions

Wind tunnel facility	M_∞	$h_{0,\infty}$ (MJ/kg)	Re (10^5 m^{-1})	U_∞ (ms^{-1})	T_∞ (K)	ρ_∞ (kgm^{-3})	p_{pitot} (kPa)	T_w (K)
CUBRC LENS-XX Run 04	12.8	21.8	2.0	6497	652	0.964E-3	39.5	300
UQ X3 Shot A-294	12.8	22.36	1.24	6498.8	1421.8	1.05E-3	68.6	300

3.2 Computational Grids

Utilizing the axisymmetry of the geometry, the simulated model was the 2-D upper half of the geometry (w.r.t. Fig. 4). The computational grids were generated using Pointwise^{12,13} and consisted of quadrilateral elements. Two grid levels were generated: coarse and fine. The coarse grid consisted of 1000 streamwise cells and 120 wall normal cells, for a total of 120 K cells, and a wall-normal spacing of 2.5 E-6 m. The fine grid consisted of 1290 streamwise cells and 325 wall normal cells, for a total of 420 K cells and a wall-normal spacing of 2.0 E-7 m. Figure 5 compares the pressure and heat flux results on the double-cone wall versus axial length for the two grid levels using the two-temperature nonequilibrium model (to be discussed later). The axial length, x , is nondimensionalized as the ratio of the axial length from the nose tip to the axial length of the upstream cone, that is, $x = (X - X_n)/L_{c1}$. Pressure, p , is nondimensionalized by $p_{pitot} = 43.3$ kPa. Heat flux, $\dot{q}$, is nondimensionalized as Stanton number, $St = \dot{q}/(\rho_\infty U_\infty h_{0,\infty})$. The coarse and fine grids show only minor differences in the regions of the peak and just after the peak. The remaining results and analysis herein will be that of the coarse grid. A more rigorous grid study will be conducted in the future.

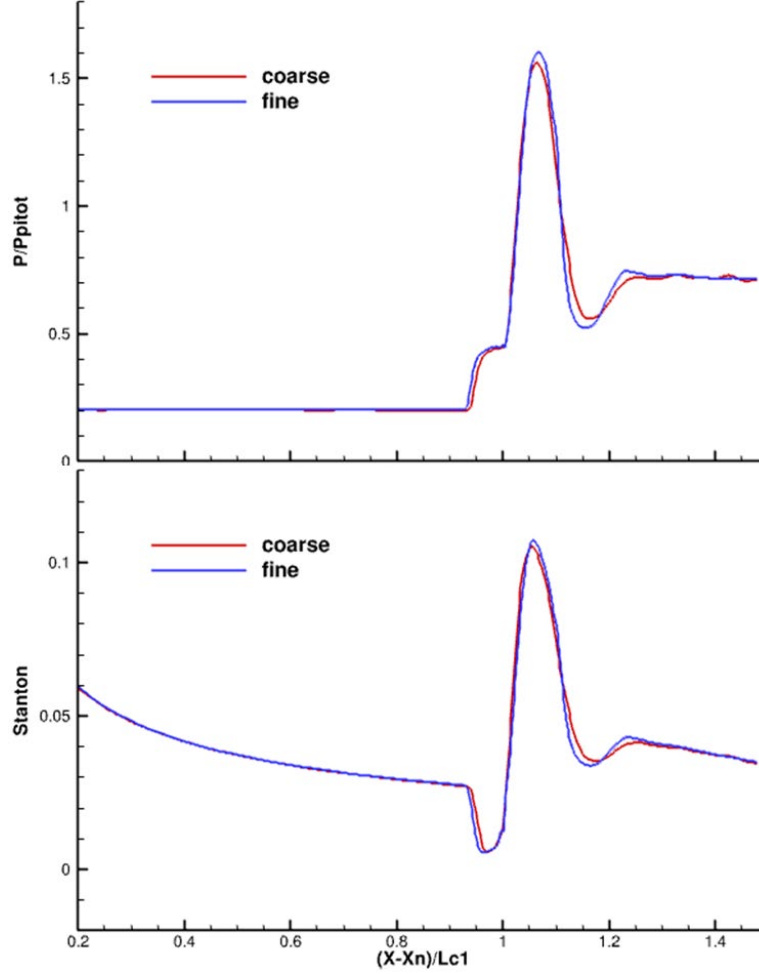


Fig. 5 Grid level comparison

3.3 Conservation Equations and Numerical Schemes

The simulation uses the commercial code CFD++.^{14,15} The numerical method solves the compressible Navier-Stokes equations for mass, momentum, and energy transport in conservative form using a finite-volume unstructured formulation. Global mass and momentum equations are purely mechanical and remain unchanged in the presence of chemical reactions and nonequilibrium effects. The energy equation is augmented to account for species diffusion effects. In addition to global mass conservation, for flow with n reacting species, $n - 1$ species mass transport equations are solved whose source terms are the species rate of formation due to chemical reactions and species diffusion. For flow with thermal nonequilibrium, a nonequilibrium energy conservation equation is solved whose source terms account for all mechanisms of nonequilibrium energy transfer, for example vibration-translation energy coupling. The convective fluxes are reconstructed using a second-order Harten-Lax-van Leer-Contact scheme¹⁶ with a

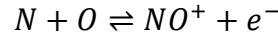
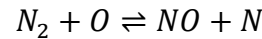
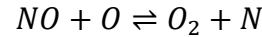
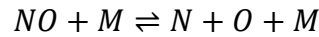
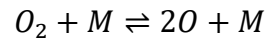
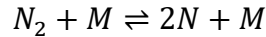
continuous total variation diminishing flux limiter. The viscous fluxes are discretized using a second-order central differencing scheme. Local dissipation was added where necessary to stabilize and converge the solution. Time stepping was performed using a “quasi-transient” approach using first-order implicit time integration with dual-time stepping consisting of a single inner iteration to advance the solution to steady-state. A timestep of 1.0E-8 s was chosen based on the min/max eigenvalues from initial test runs.

3.4 Physical Gas Models

Two gas modeling approaches were used. The first is the simpler perfect gas (PG) model. This is the typical assumption for low enthalpy and/or lower speed flows. While it does not capture all the relevant physics for this test case, it is presented here for comparison purposes. In this case, the gas was assumed to be a single-specie non-reacting perfect gas, and the temperature-kinematic viscosity relation was modeled using Sutherland’s law.¹⁷

The second approach is a multi-specie reacting flow with chemical nonequilibrium and thermal nonequilibrium (TNE). This is generally the highest-fidelity approach available for continuum gas physics. For the chemically reacting flow, the freestream was assumed to be air consisting of 77% nitrogen and 23% oxygen. Finite-rate chemical kinetics utilized a seven-specie six-reaction reduced mechanism, valid for temperatures up to 9000 K¹⁸:

Species: $N_2, O_2, NO, N, O, NO^+, e^-$



Here, M is a “third body” species that acts as a collision partner providing additional energy for dissociation, or carrying away energy released during recombination, but is itself unchanged. The rate of formation of a given species is based on the law of mass action,¹ where the forward reaction rate k_f for each reaction was calculated using the modified Arrhenius correlation $k_f = C\bar{T}^\eta e^{-E_a/R\bar{T}}$, where the frequency factor C , temperature exponent η and activation energy E_a are experimentally

determined, R is the universal gas constant and $\bar{T}$ is defined below. The backward reaction rate k_b was computed from the equilibrium condition $k_{eq} = k_f/k_b$. The limits of frozen and equilibrium flow are implied as the reaction rate tends to zero and infinity, respectively.

In modeling equilibrium flow, the temperature T corresponds only to the translational energy mode; it determines the frequency and energy of collisions, and therefore vibrational excitation and chemical reactions. For nonequilibrium flows in which internal energy modes become activated, one approach to modeling is the two-temperature nonequilibrium model (TTNE). The model assumes that (1) translational and rotational energy modes are in equilibrium corresponding to temperatures $T = T_t = T_r$, and (2) vibrational, “heavy species” electronic excitation and “free electron” translational energy modes are in equilibrium corresponding to temperatures $T_v = T_{ex} = T_e$. That is, energy modes are grouped into two, one corresponding to T_r and one corresponding to T_v . Therefore, the additional nonequilibrium energy conservation equation is essentially an equation for vibrational energy transport whose source terms account for energy coupling (that is, energy transfer) between modes.

The vibration-translation coupling source term is modeled according to Landau-Teller¹⁹ with species vibrational relaxation times from Millikan and White²⁰ and the high-temperature correction of Park.^{21,22} The model solves a vibrational energy rate equation derived based on a harmonic oscillator of the form $De_v/Dt = (e_v^{eq}(T) - e_v(T_v))/\tau$, where τ is the vibrational relaxation time and superscript eq represents the equilibrium state. The limits of frozen and equilibrium flow are implied as τ tends to infinity and zero, respectively. Other energy couplings may be included, but not discussed here because they are presumably less significant for this test case.

In flows with both vibrational and chemical nonequilibrium, there is a coupling between the two, for example, molecules in higher vibrational energy states are more readily dissociated by molecular collisions, and similarly, dissociation preferentially depopulates higher vibrational energy levels affecting the instantaneous vibrational energy and relaxation time.¹ One approach to the vibration-dissociation coupling is based on the popular Park model.²³ The dependency of dissociation on vibrational excitation is accounted for by assuming that the forward reaction rate is a function of a geometric mean temperature $\bar{T} = T_t^a T_v^b$, where a and b are empirically determined. The backward reaction rate is a function of T_t only. If vibrational equilibrium exists, $T_v = T_t$ and $\bar{T} = T_t = T$, as expected. If $T_v > T_t$, then $\bar{T} > T_t$ thereby increasing the reaction rate relative to the assumption of vibrational equilibrium, and vice versa.

For high-temperature multi-species gas dynamics, models for fluid transport and thermodynamic properties are different than that typically assumed for perfect gas flows, for example. The viscosity and thermal conductivity transport properties were computed using the Gupta-Yos models.²⁴ Species diffusion was modeled using a modified version of Fick’s law with either a constant laminar Schmidt number or a binary diffusion model. Here the former was used with Schmidt number $Sc = 0.525$. Thermodynamic quantities are computed based on three properties that vary with temperature: species specific heats at constant pressure, species specific enthalpies and species specific entropies. They are described by the “NASA-7” polynomial curve fits across five temperature ranges up to 30,000 K.²⁴ Finally, the wall was assumed to be a no-slip, non-catalytic, isothermal, cooled wall at 300 K.

3.5 Results

Figures 6–8 compare the TTNE and single-specie PG flow fields for the double-cone configuration. Shown are streamwise velocity, temperature (translational), and normalized strain rate. The plots show salient features of the SBLI interaction, viz, the shock structures, the separation event, and downstream recovering boundary layer. There are two primary shock waves: the first is an oblique shock wave produced by the upstream cone, and the second is a shock produced by the downstream cone that is initially curved and eventually straightens to an oblique shock further downstream. In the case of TTNE, the first upstream shock impinges on the second downstream shock just after the juncture. A shear layer is observed stemming from this intersection location that separates hotter slower-speed fluid below the shock wave from cooler higher-speed fluid closer to the wall. The adverse pressure gradient in the post-shock region of the second primary shock feeds upstream through the subsonic portion of the viscous boundary layer and produces a relatively small region of low-speed separated flow. Secondary shocks arise from the separation and reattachment points. These secondary shocks intersect each other and also intersect the second primary shock at short distances after the juncture.

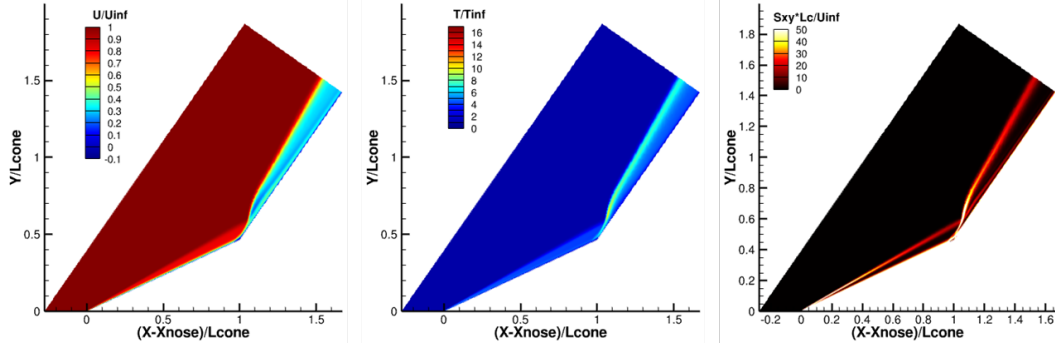


Fig. 6 Flow fields using TTNE model: streamwise velocity, temperature, and strain rate

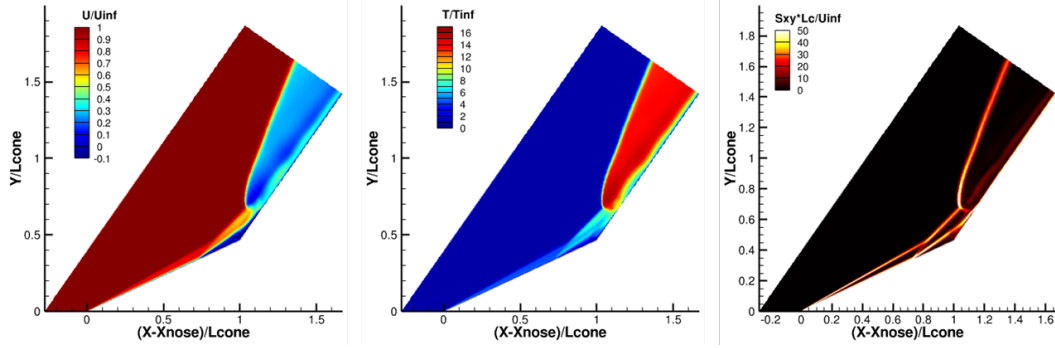


Fig. 7 Flow fields using PG model: streamwise velocity, temperature, and strain rate

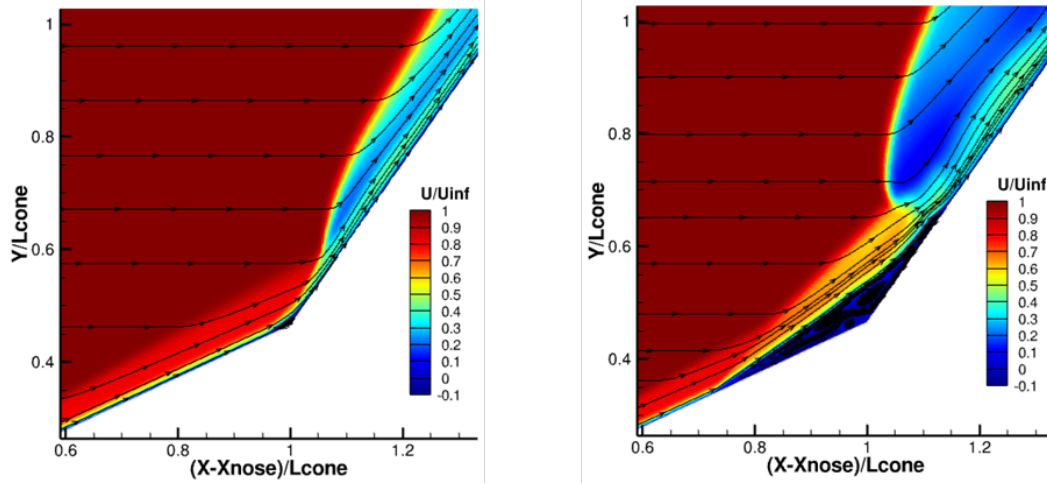


Fig. 8 Zoom of corner separation showing streamwise velocity: TTNE (left) and PG (right)

In the case of PG, the separation bubble size is much larger, presumably because of stronger adverse pressure gradients due to the larger angle of the primary shock on the second cone. Unlike the TTNE case, the upstream primary oblique shock impinges on the secondary separation shock. The separation shock intersects the downstream primary shock on the second cone, producing a transmitted shock that impinges on the surface close to the reattachment point of the separation bubble. A

shear layer is again observed stemming from this triple intersection point, separating hotter slower-speed fluid below the shock wave from cooler higher-speed fluid closer to the wall.

There is a remarkable difference between the TTNE and PG flow fields. The TTNE model is expected to better model the physics of the problem in that it accounts for high-temperature gas effects. The PG model is presented here for comparison. The size of the separation bubble for the TTNE model ($L_{sep} \approx 0.08$) is significantly smaller than that of the PG model ($L_{sep} \approx 0.41$). Here, separation length, L_{sep} , is taken as the axial distance from the separation point to the reattachment point (normalized by L_{c1}) as determined by the precipitous fall and peak rise of the wall Stanton number. The X3 experiment by contrast indicates an average $L_{sep} \approx 0.21$.

Figure 9 compares the translational and vibrational temperature fields for the TTNE model. Figure 10 shows the species mass fractions. The post-shock region on the upper cone is generally much cooler for the TTNE model than the PG model, which is approximately 3–4 times hotter. This is likely due to energy transfer from the flow to vibrational energy and to endothermic dissociation reactions. There is comparatively little vibrational excitation and dissociation in the post-shock region of the upstream cone. At the juncture and in the post-shock region of the upper cone, where temperatures are high, vibrational excitation and chemical reactions significantly increase. Both translational and vibrational temperatures reach a maxima in the region where the two primary shock waves intersect just following flow reattachment. Along the shock front, vibrational excitation is high and relaxes toward the surface. Diatomic nitrogen, N_2 , and oxygen, O_2 , dissociate significantly post-shock. The reactions result in large populations of monoatomic O and N , and modest concentrations of nitric oxide NO . Ionization effects are comparatively small given the low concentrations of nitric oxide ions, NO^+ , and free electrons, e^- . Traversing normal from the shock front to the cone surface, dissociation of N_2 and O_2 increase rapidly, yielding increasing concentrations of O , N , and NO close to the shock front and reaching a peak between the shock front and the cone surface. Approaching the cooled wall, recombination yields a layer of increased concentration of N_2 along the surface that almost reaches the freestream value, while decreasing N to negligible values. Concentrations of NO also decrease rapidly toward the surface; however, a high concentration of NO develops near the shock intersection region, which permeates downstream in the near wall region, and eventually decreases further downstream. Concentrations of O remain high and concentrations of O_2 remain low close to the cone surface. Ionization produces NO^+ and e^- , albeit much lower populations, that also increase rapidly near the shock front and relax toward the surface where they reach almost zero concentrations.

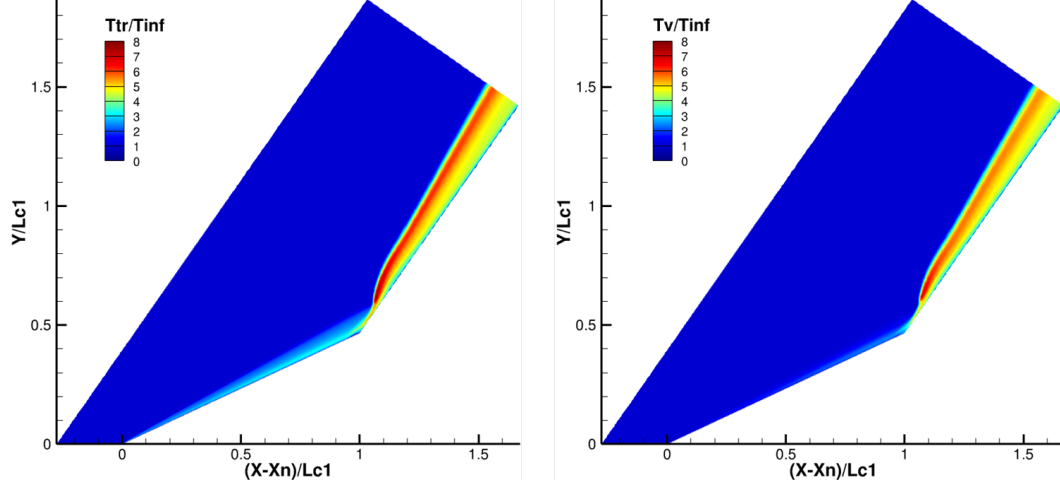


Fig. 9 Temperature fields using TTNE model: translational (left) and vibrational (right)

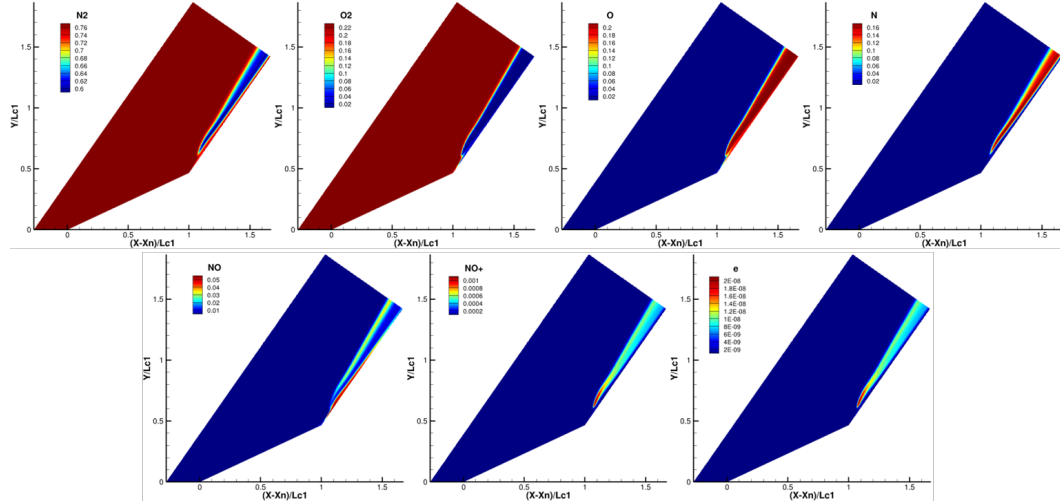


Fig. 10 Species mass fractions using TTNE model (note contours scales are different)

Figure 11 shows streamwise wall measurements of pressure, heat flux, skin friction ($C_f = \tau_w / [0.5 \rho_\infty U_\infty^2]$), and cell Reynolds number ($Re_{cell} = [\rho_w U_1 dy_1] / \mu_w$), where τ is shear stress, μ is the dynamic viscosity, dy is the wall normal cell spacing, subscript w refers to the wall and subscript 1 refers to the first cell centroid off the wall. The UQ X3 wind tunnel data was sampled at various axial and spanwise locations. The wind tunnel data presented here is time-averaged and span-averaged. Both PG and TTNE models show good agreement with each other and with the experiment for wall measurements on the upstream cone ($x < 0.7$), although heat flux is slightly underpredicted. The TTNE models predict a smaller separation bubble in which separation occurs further downstream and reattachment occurs more upstream than the PG model as well as the X3 experiment. The PG model grossly overpredicts the peak pressure and heating near the reattachment

location, and predicts their peak locations further downstream than experiment. The TTNE model shows excellent agreement for peak pressure and slight underprediction of peak heat flux. Interestingly, both models predict similar peaks in wall shear stress, although at slightly different locations. In the downstream boundary layer on the second cone, both TTNE and PG models capture the wall pressure immediately following reattachment, but both underpredict the heat flux compared to experiment. Also of note, the PG model shows oscillations in pressure, heat flux, and skin friction downstream of reattachment, likely due to the presence of a reflected shock train through the high-speed region between the shear layer and the surface of the upper cone.

The cell Reynolds number can be used in laminar flows as one measure of grid convergence. A more extensive grid convergence study will be conducted in future simulations. The plot in Fig. 11 for the coarse grid illustrates two important considerations when using this metric. First, in the region of reattachment, the cell Reynolds number spikes by 6–8 times the upstream value and this region is therefore the determining factor for near-wall grid resolution. This is likely due to the high-velocity and temperature gradients in this region. Second, the TTNE model requires finer grid resolution if one is to match the cell Reynolds number of the PG model.

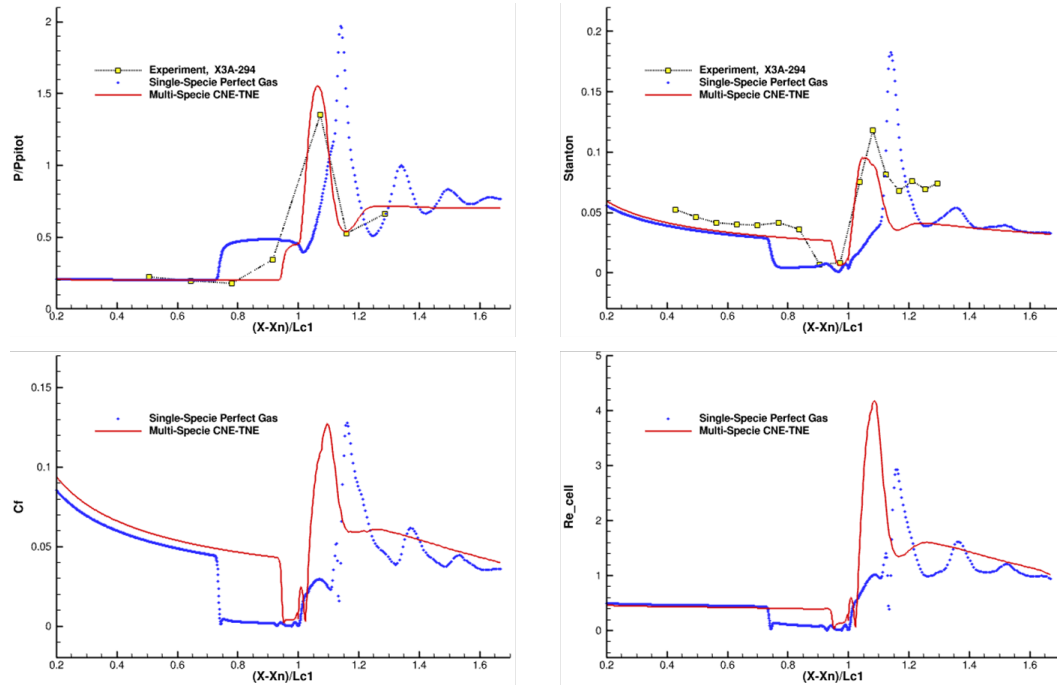


Fig. 11 TTNE vs. PG: pressure, Stanton number, skin friction, and cell Reynolds number

4. Conclusion

A computational investigation was conducted for the high-enthalpy hypersonic double-cone test case. The double-cone has been tested extensively in the UQ X3 and CUBRC LENS-XX wind tunnels, which have provided rich data sets for modeling validation. The simulated test condition herein was the highest enthalpy condition available, and thus was expected to be the most challenging to simulate accurately. The geometry and flow conditions specifically matched the UQ X3 experiment. State-of-the-art modeling employed full Navier-Stokes with multi-specie finite-rate chemical kinetics, vibrational relaxation, coupling of vibration, and dissociation via a two-temperature nonequilibrium approach, and modeling of viscosity, thermal conductivity, and diffusion transport properties specifically geared for high-temperature gases. Flow-field solutions showed complex interactions of the primary shock waves with the viscous boundary layer producing a separation bubble at the juncture, multiple secondary shocks, and high-temperature and velocity gradients at the regions of flow reattachment and shock intersections just downstream of the juncture. The high-temperature post-shock region on the upper cone showed a high degree of dissociation, vibrational excitation, and thermochemical nonequilibrium. Predicted surface pressures matched well with experiment, while surface heat flux indicated an underpredicted separation bubble size and underpredicted heating in the post-shock region on the upper cone. The peak heat flux and its location was, however, reasonably well predicted just downstream of the juncture on the upper cone. The use of the perfect gas model clearly emphasizes the need for modeling high-temperature gas effects. The perfect gas model retains more energy in the flow, drastically changing the shock structures, and significantly overpredicting the extent of separation and peak heating.

A future report will present simulations of additional enthalpy conditions, all in the Mach 11–13 and 3–6.5 km/s ranges. Detailed trade studies will be conducted, including those pertaining to nonequilibrium model parameters, reaction mechanisms, fluid transport properties, grid refinement, flux schemes, wall boundary conditions, and transient effects. The effect of 3-D spanwise relaxation will be explored. The levels of uncertainty in both CFD and experiment will be quantified. A detailed analysis will be conducted of the shock interactions with the viscous boundary layer, including the separation and reattachment processes that lead to the observed local maxima in thermochemical effects, pressure, and heat flux.

Development of hypersonic weapon systems relies heavily on CFD due to the complexity and cost of conducting hypersonic ground and flight experiments. It is

therefore necessary to evaluate current capabilities and improve physical models to increase prediction accuracy while reducing modeling uncertainties and excessive design margins. This report illustrates that, while there have been significant advances in numerical methods and physical gas models, there are still needed improvements for application to high-enthalpy hypersonic flows.

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List of Symbols, Abbreviations, and Acronyms

2-D	two-dimensional
3-D	three-dimensional
CFD	computational fluid dynamics
PG	perfect gas
SBLI	shock–boundary layer interactions
SSI	shock–shock interactions
TNE	thermal nonequilibrium
TTCP	The Technical Cooperation Program
TTNE	two-temperature nonequilibrium model
UQ	University of Queensland

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