Middle East Technical University
Ankara, Turkey

12th International Planetary Probe
June,15-19, Cologne, Germany

ANALYSIS OF HYPERSONIC NON-EQUILIBRIUM REENTRIES WITH NEWTON-GMRES METHOD

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ABSTRACT

The aim of this study is to simulate hypersonic flow field around the Apollo Command Module during the reentries of the Earth by using Newton– GMRES method. Modelling high speed hypersonic flow such as re-entries requires consideration of all physical phenomena and that of appropriate numerical modelling. Because of high energetic species, real gas assumption is used to define species state characteristics instead of ideal gas assumptions. Chemical, thermal and vibrational non-equilibrium modelling is the main consideration of this study.

INTRODUCTION

The gravitational accelerations yield reentries with high spend and high energy. With an increasing temperature, the characteristics of flow field change substantially. The dissociation reactions of oxygen starts about 2000K and that of nitrogen starts around 4000K in the reentries of the Earth atmosphere. However, typical maximum temperature during reentries is approximately 25000K. At this temperature, there are ionization and impact reactions in addition to dissociation and exchange reactions. Also, real gas and nonequilibrium effects should be considered for the sake of accuracy of flow solver. There are many models and studies to model thermochemical and physical nonequilibrium with various assumptions

Park's two temperature model [1] is used in this study because of fast interaction between translational-rotational and vibrational- electronic energy modes. To model chemical nonequilibrium different forward rate constants and different equilibrium constant calculations are examined. For the vibrational relaxation, harmonic oscillation assumption and Landau Teller relaxation with modifications are examined [2]. For the thermal nonequilibrium, real and ideal gas assumptions were examined with curve fitted specific heat capacity, entropy and enthalpy values. The simulation of flow field is obtained by using Newton GMRES which is an inexact implementation which satisfy linearity of equation by using GMRES methods. Basically, Newton- GMRES method is an inexact Newton method where norm of the local linear residual is reduced in each step. Also, Newton method is used to evaluate translational and vibrational temperature. Three dimensional Apollo Command Module is chosen as geometry. The aim of this study is to simulate and to compare simulation of the reentries to Earth atmosphere with different assumptions.

METHODS

Mass, momentum, total energy, vibrational energy and species mass conservation equations are written as in form of Euler equation.

$$R(w) = \frac{\partial F\,(w)}{\partial \xi} + \frac{\partial G\,(w)}{\partial \eta} + \frac{\partial H\,(w)}{\partial \zeta} - \hat{S}$$

Newton's method:

$$R^{n+1} = 0 \text{ and } \left(\frac{\partial R}{\partial w}\right)^{n} \Delta w^{n} = -R(w^{n})$$

Inexact Newton's method:

$$\left\| \breve{R}^{n}(\breve{w}) + \left(\frac{\partial \breve{R}}{\partial \breve{w}}\right)^{n} \Delta \breve{w}^{n} \right\| = \mu \left\| \breve{R}^{n}(\breve{w}) \right\|$$

** Approximate solution of exact method
** No need to evaluate Jacobian matrix
** Matrix free
** CPU time efficiency

Chemical Non- Equilibrium

species : N_2, O_2, N, O, NO, N_2^+, O_2^+, N^+, O^+, NO^+ and e (5 and 11 species)

$$k_{f,i}(T_r) = A_i T_f^{\beta_i} e^{-\frac{E_i}{R_u T_r}} \quad , \quad k_{b,i} = \frac{k_{f,i}}{k_{eq,i}}$$

Gibb's free energy minimization: $k_{eq,i} = k_p(T_b)\left(\frac{R_u T_b}{P_{atm}}\right)^{\alpha}$

Park's curve fitted equation: $k_{eq,i} = e^{(c_1 z^{-1} + c_2 + c_3 \ln z + c_4 z + c_5 z^2)}$

Vibrational Non- Equilibrium:

$$E_{v,s} = \frac{R_s \theta_{v,s}}{\left(e^{\frac{\theta_{v,s}}{T_v}} - 1\right)} \qquad \dot{w}_v = \dot{w}_{v-c} + \dot{w}_{v-t} + \dot{w}_{v-v}$$

$\dot{w}_{v-c}$, interactions of vibrational temperature and dissociation reactions
**Park's controlling temperature ($T_c = \sqrt{T_{tr} T_v}$) is used for calculation of the forward reaction rate constant.

$\dot{w}_{v-t}$, modelling energy exchange vibrational energy and translational energy
**Landau-Teller formulation with correction of Park is used for modelling.

$\dot{w}_{v-v}$, energy exchange between molecules having different vibrational energy levels

RESULTS

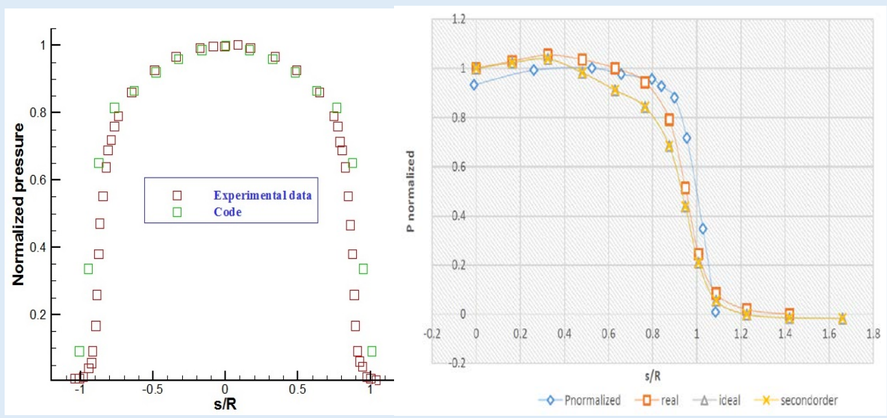
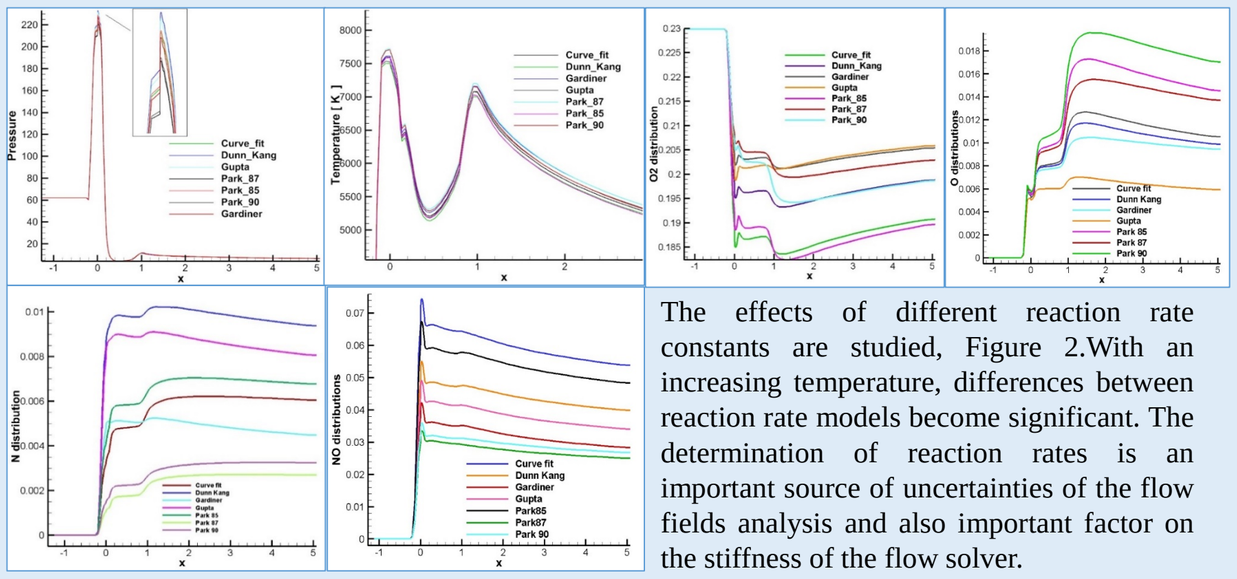


Figure.1 Comparisons of normalized pressure distribution with different assumptions (M=10.18)

Surface pressure around the module are compared with the wind tunnel tests of the small scale version of ACM. The various results for normalized pressure at stagnation line are given in Murray study [3]. These results are obtained from Bertin's [4] and Marvin's [3] wind tunnel experiments.



The effects of different reaction rate constants are studied, Figure 2.With an increasing temperature, differences between reaction rate models become significant. The determination of reaction rates is an important source of uncertainties of the flow fields analysis and also important factor on the stiffness of the flow solver.

Figure.2 Comparisons of effects of different constants to calculate forward reaction rates on flow variables

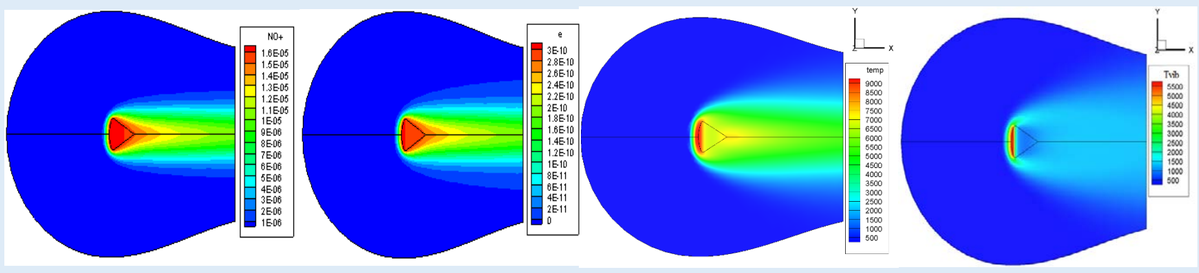


Figure.3 NO+ and electron countours as well as translational and vibrational temperature countours.

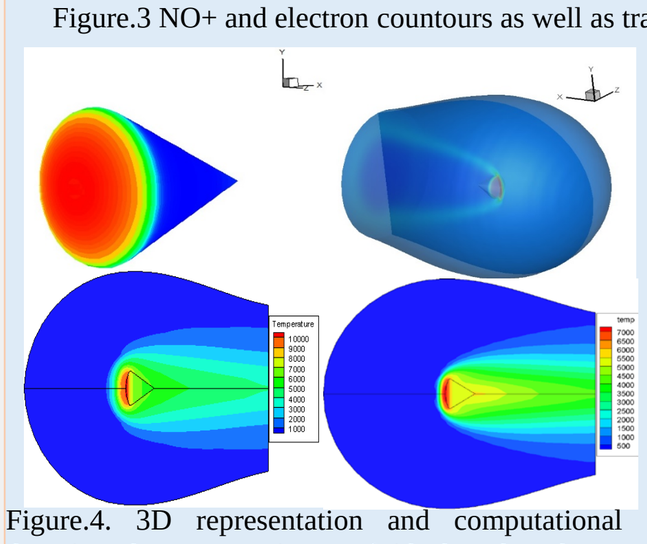


Figure.4. 3D representation and computational domain; also, comparisons of ideal and real gas assumptions in terms of T

In Figure 3, ionized species and electron mass fractions can be seen. Moreover, translational and vibrational temperature countours are given. Vibrational temperature countours are similar to translational temperature; however, the peak values are different, and vibrational interactions continue at the wake of geometry. The whole geometry and computational domain are shown in Figure4. Also, in this figure, temperature values from ideal (left) and real (right) gas assumptions are given. In the blunt bodies, shock standoff distance is reduced due to real gas effects [1]. Also, there are differences in surface heating rates, shock characteristics and flow compositions.

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ACKNOWLEDGEMENTS

This research is supported by The Scientific and Technological Research Council of Turkey (TUBITAK).