DSMC solver for an optimized Space Crew reentry Orbital Vehicle

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Abstract

An algorithm for solving the flow around the Orbital Vehicle at the time of its re-entry has been formulated. The physics behind the behavioral pattern of a re-entry vehicle has been a topic of research for a long time. It has been seen that a blunt nose configuration is preferred over a sharp nose configuration. Direct Simulation Monte Carlo method has been used to develop a code in Matlab to simulate the flow. The main equation governing the flow is Maxwell-Boltzmann equation which is due to consideration of rarefied flows at altitudes beyond 80 km. A unique method of introducing the coordinates of the geometry is used. The results for Knudsen number 0.03 were compared with Ansys results. Also an optimized model of the Orbital Vehicle is suggested without compromising the purpose, which can be used for further studies and development.

Introduction

The development of the Indian Orbital Vehicle (OV) began in 2006. The plan was to design a simple vessel similar to the Mercury – class spacecraft [1] with an endurance of about a week in space. It was designed to carry three astronauts and to land in water upon re-entry. The design was finalized by March 2008, and was submitted to the Government of India for funding. It was launched successfully on 18 December 2014 from the Second Launch Pad of the Satish Dhawan Space Centre, by a GSLV Mk III rocket. Various methods are used to analyze the flow past re-entry vehicles and DSMC is one of them.

To simulate the flow around the OV during reentry, an independently developed Matlab code using the basic principles of Direct Simulation Monte Carlo (DSMC) method is used. Transition from rarefied to continuum regime occurs when the OV reenters the Earth. The flow is considered rarefied when the altitude is above 80 km from the mean sea level of the earth [2].

In rarefied flows [3], continuum model loses its validity and must be replaced by a suitable molecular model [2]. The mathematical model at this level is the Maxwell-Boltzmann equation [4]. The degree of rarefaction of gas is expressed through the Knudsen number (Kn) given by the expression,

$$\mathrm{Kn} = \frac{\lambda}{L}, \qquad (1)$$

where, λ – Mean free path of the molecules [5]
L – Length scale of the flow.

In the continuum regime, the Knudsen number (Kn) is a function of Mach number, geometric scale, density and temperature. The length scale L can be expressed as scale length of macroscopic gradients. Validity of Navier-Stokes equation stops when Knudsen number crosses 0.1. Beyond Kn>0.1, the flow is solved using Boltzmann equation [2].

$$f(\nu) = \sqrt{\left(\frac{m}{2\,\pi\,k\,T}\right)^{3}}\ 4\,\pi\,\nu^{2}\,e^{-\left(\frac{m\,\nu^{2}}{2\,k\,T}\right)} \tag{2}$$

where, m – Mass of the molecule
k – Boltzmann constant
T – Absolute Temperature
ν – Velocity of the particle

The Maxwell-Boltzmann equation as seen in Eq. 2, which forms the basis of the kinetic theory of gases, defines the distribution of speeds among the individual molecules for a gas at a certain temperature [2]. It is assumed that gas molecules are in quasi steady state.

During expansion or collision of molecules, the velocities of individual molecules may change with time. However, the statistical distribution of velocities would remain the same as Maxwell-Boltzmann distribution [6].

A common example of flow regime, where the Boltzmann equation would be necessary is the operation of flight vehicles in the upper atmosphere. For space exploration mission, various advanced technologies have been developed that enables atmospheric re-entry and flight at extreme velocities. As the range and the re-entry velocity of the ballistic missiles increased, heating became a serious problem [7]. Allen et al of the National Advisory Committee for Aeronautics (NACA), in 1951 proved that a blunt shape made the most effective heat shield. Their results showed that the heat load experienced by an entry vehicle was inversely proportional to the drag coefficient, i.e. the greater the drag, the less the heat load [8]. If the re-entry vehicle is made blunt, 90 percent of the friction heat would be dissipated through the bow shock wave [8]. Hence, blunt body configuration became the most common geometries employed for re-entry into planetary atmospheres or for space exploration missions to other celestial bodies [9].

Intermolecular collisions in dilute gases are likely to be binary collisions involving just two molecules because the probability of ternary and higher order collisions is very less in a dilute gas [10]. Only elastic collisions are considered in the current study, where momentum and energy are conserved. The assumption of elastic collisions implies that there are no losses due to the collisions. Helium is used as the working gas for simplicity [11]. Even for analyzing lower Knudsen number, neglecting ternary and higher order collisions is efficient [6].

Algorithm

The well-known shock tube problem [12] is considered as flow regime to solve the flow past the OV. The shock tube consists of the gas helium on one side with a complete vacuum on the other side, separated by a diaphragm as shown in Fig. 1.

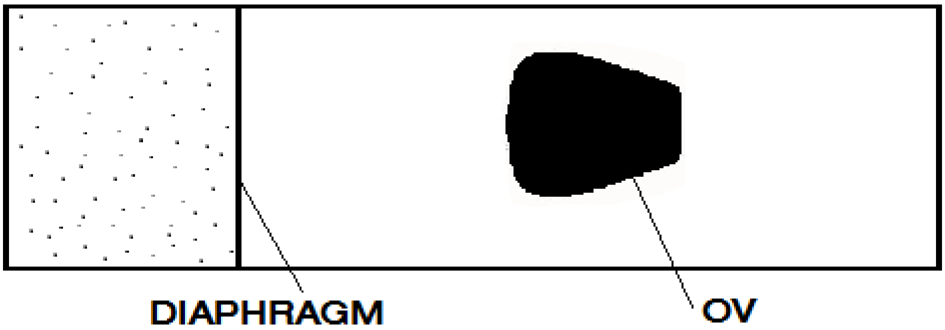


Figure 1. Shock Tube with the Orbital vehicle in it

The region where the helium gas is present is called the constrained region. The particles are well mixed in the constrained region before they are set to expand. The shock tube is divided into cells with a unique cell id. Using Eq. 2, the velocity of the particles was distributed initially and their random coordinates are given. When the particles collide, their pre-collisional velocities are replaced by the post-collisional velocities, thereby conserving the momentum. The geometry of the

OV is incorporated in the code using the coordinates obtained from [13]. The simple panel geometry obtained from [13] checks whether the particles crosses the panel or not using the slope of the nearest particle and the corresponding panel. In that way, the collision of the particles with the wall is determined.

The results from this code are compared with the results from the standard computational package, Ansys.

Results

The code was ran on an Intel Core I5-2450M processor computer with 4 GB RAM at 2.5 GHz in Matlab version R2009b. These results were compared with Ansys results, which solved the flow using density based solver. The mesh used in the Ansys is shown in Fig. 2.

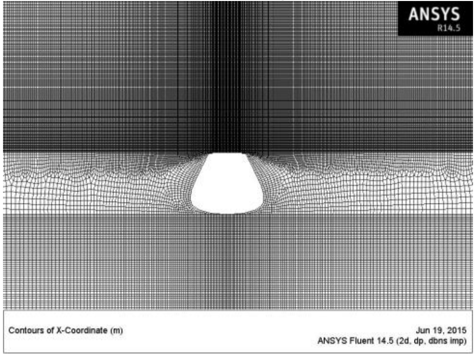


Figure 2. Mesh generated in Ansys

The Mach numbers in both the cases are compared in Fig. 3.

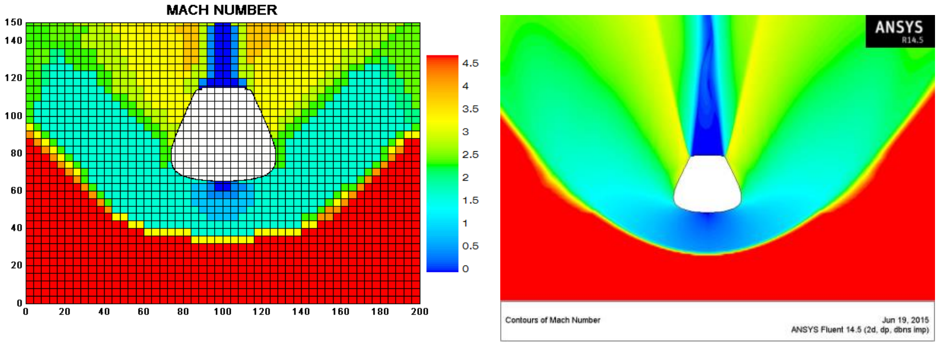
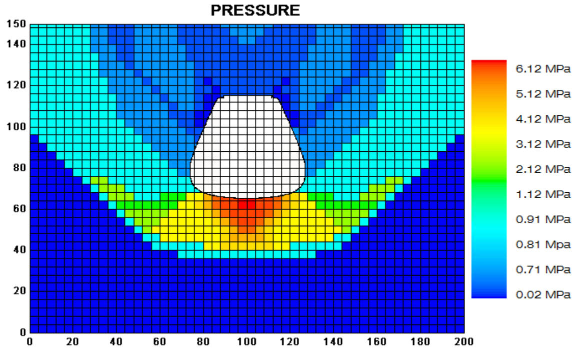


Figure 3. (From left) Mach number from DSMC, Mach number from Ansys

Also the variation of static pressure and static temperature are shown in Fig. 4 and Fig. 5 respectively.



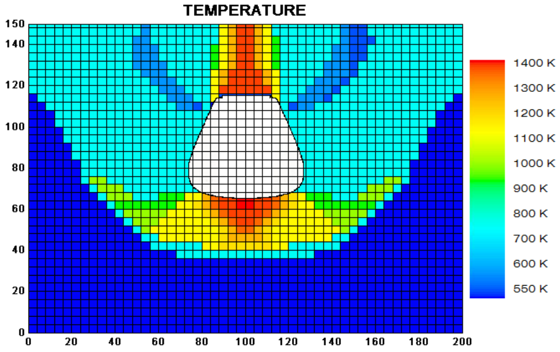


Figure 4. Static Pressure from DSMC

Figure 5. Static Temperature from DSMC

Discussions

The results from DSMC Matlab code and the Ansys are very much similar for the Knudsen number of 0.03. The Mach number of the flow is 4.5 and the surface temperature of the vehicle is 550 K. The small variation in pattern in Fig. 3, can be attributed to the limited number of cells used in DSMC Matlab code. Matlab code used 30000 cells, whereas in Ansys 265538 cells were generated. The cells were limited due to constrain in computational time and lack of high performance computers. Also the other reason could be the random motion introduced in the code to initialize the flow.

The analysis took 28 hours to compute in Matlab after incorporating accelerating schemes developed by Krishnamurthy et al [14]. Now with this, the geometry can be optimized to provide better aerodynamic efficiency.

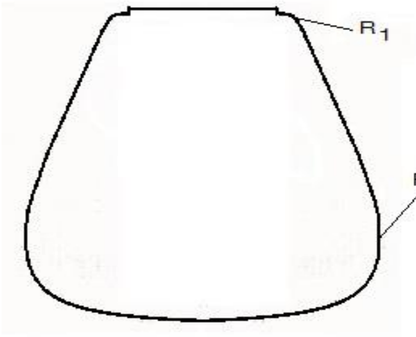


Figure 6. Radii of curvature pointed out in the geometry

To optimize the geometry, two parameters R_1 and R_2 are chosen. R_1 and R_2 are the radii of curvature of the original geometry at two distinct locations as seen in Fig. 6. These parameters are altered, without changing the inner volume or any abrupt change in the gradient and checked for the maximum temperature on the surface of OV.

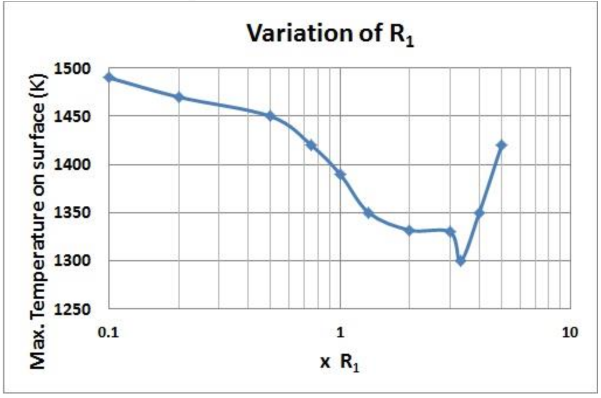


Figure 7. Variation of R_1

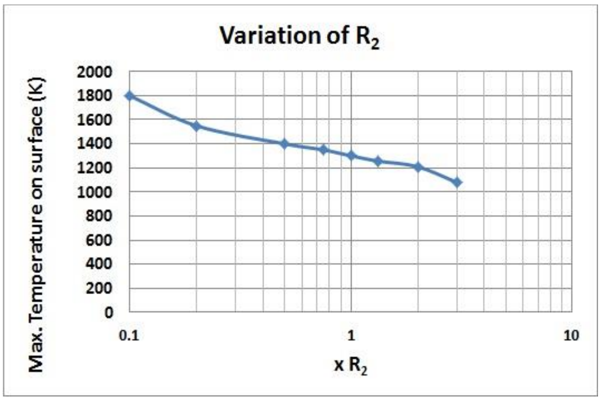


Figure 8. Variation of R_2

From the above Fig. 7, the optimized value of R_1 can be taken as 3.33 times the initial value of R_1. Fixing that as the base radius R_1, radius R_2 was varied. It showed an expected trend as predicted by Allen et al in [8]. But the base radius R_2 cannot be extended limitlessly as it increases the volume and mass.

Hence an optimized value of increasing the initial R_1 by a factor of 3.33 and increasing the initial R_2 value by a factor of 1.25 is suggested in this work.

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