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AEROTHERMAL ANALYSIS OF HYPERSONIC FLOW AROUND A CYLINDER

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ABSTRACT

The results of aero-thermal analysis of hypersonic flow over a cylinder is presented in this paper. The flow regimes in hypersonic flow is rarefied and the continuum concept becomes invalid. The Direct Simulation Monte Carlo (DSMC) is a particle simulation method suitable for the analysis of rarefied flow. In this work DSMC simulation is carried out using an open-source code dsmcFoam available in OpenFOAM tool kit. The code has been validated by solving supersonic flow over a flat plate for which results are reported by Bird[1]. The hypersonic flow around a cylinder has been solved for different Knudsen number. The complex flow phenomena are analyzed and discussed.

NOMENCLATURE

Kn	Knudson number
M	Mach number
V	Velocity (m/s)
T	Temperature (K)
n	Number density
m	Molecular mass (kg)
ω	Temperature coefficient of viscosity
d	Diameter (m)

Subscript

∞	Free stream condition
w	Wall
ref	Reference condition

1. INTRODUCTION

In the hypersonic flow, the shape/geometry of the body is a critical consideration in design. Aero-thermodynamic heating is inversely proportional to the square root of the radius at stagnation point (bluntness). The study of flow phenomena and surface properties are important in hypersonic vehicle design. Hypersonic vehicles experience wide range of flow regimes in its trajectory. The continuum concept is no longer valid in the near wall region, especially in the rarefied flow condition. The ratio of mean free path of the gas molecule and characteristic length (Knudsen number) is the parameter which defines range of rarefaction in a flow. The solution of Navier-Stokes equation becomes invalid in the rarefied regimes (Kn>0.1). The solution of Boltzmann equation is valid in all flow regimes. The complexity in the solution of Boltzmann equation led to the development of a simple and computationally affordable technique called Direct Simulation Monte Carlo (DSMC) Method[1] to predict the flow. DSMC method is a statistical approach which emulate the physical processes modeled by Boltzmann equation. DSMC is practically feasible as compared to the molecular dynamics simulation. In this paper analysis of hypersonic flow around a cylinder is carried out for different Kn values at a Mach number of 10. The flow phenomenas and surface parameters are analyzed and reported.

2.DSMC METHOD

DSMC method is a particle based simulation in which a simulated molecule, represent a much larger ensemble of molecule tracked through space and time. The movement of particle and collision between particles are computationally decoupled. The movement of each particle is linear in nature as prescribed by its velocity vector and time-step increment. The reorientation in the particle trajectory occurs as a results of collision with wall and intermolecular collisions. The particle motion and surface collision are deterministic and intermolecular collisions are probabilistic. The collision rate is set same as that of kinetic theory of gas and probability of collision between collision pairs is find out by acceptance-rejection method. The collision can be model based on available phenomenological modes. The macroscopic properties can be found out by taking the ensemble average of the properties of the particles.

2.1 dsmc FOAM

OpenFOAM is an opensource fluid flow solver based on object oriented C++ modules and includes variety of solvers which are capable of handling most of the physical problems. dsmcFoam (DSMC solver available in OpenFOAM) has the following capabilities viz. steady and unsteady simulations by proceeding through small time steps, capability to simulate arbitrary 2D and 3D geometries, ability to define symmetry plane and cyclic boundaries, arbitrary number of gas species can be included in the simulation, free stream flows over the obstacles. The Larsen-Borgnakke model and and variable hard sphere (VHS) model for DSMC collision simulation are available in the module.

2.2 VALIDATION OF dsmcFOAM

dsmcFOAM is validated before it is being used for the present analysis. Flow of nitrogen gas over a horizontal flat plate with 1m length having Kn=0.0143 is seems to be in continuum regime, but the leading edge of the plate is of negligible dimension, thereby the flow at large speeds becomes rarefied flow. Shock generation on the leading edge, velocity slip and temperature jump on the surface will test the potential of dsmcFoam as a rarefied gas flow solver. This case is validated with the results available in Bird [1].

TABLE 1. MOLECULAR PROPERTIES

Tref(K)	ω	dref(m)	m(kg)
273	0.74	4.17×10^{-10}	4.65×10^{-26}

TABLE 2. BOUNDARY CONDITIONS

M∞	V∞(m/s)	T∞(K)	Tw(K)	n∞
4	1347.6	273	500	1×10^{20}

The molecular properties of nitrogen gas and boundary conditions associated with the flow are listed in the table 1 and table 2. The results obtained are plotted over the results of Bird[1] for comparison are shown in figures 1-4.

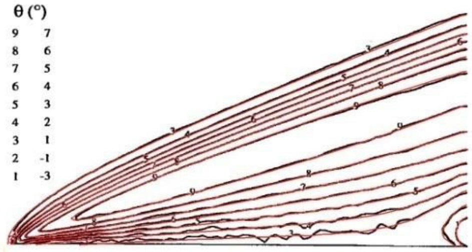


FIGURE 1. CONTOURS OF CONSTANT FLOW ANGLE OVER FLAT PLATE

(red lines-from dsmcFoam, black lines-from Bird[1])

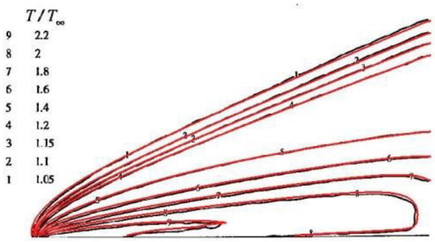


FIGURE 2. NON-DIMENSIONALISED TEMPERATURE CONTOURS OVER FLAT PLATE
(red lines-from dsmcFoam, black lines-from Bird[1])

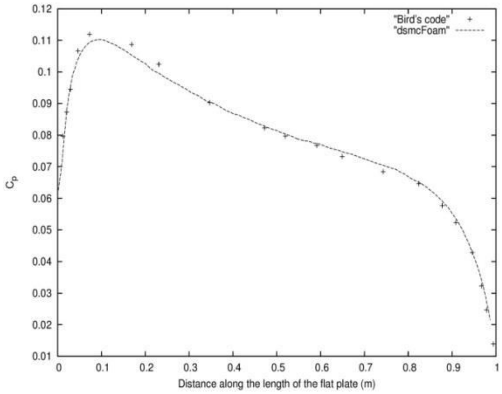


FIGURE 3. COMPARISON OF COEFFICIENT OF PRESSURE(Cp)

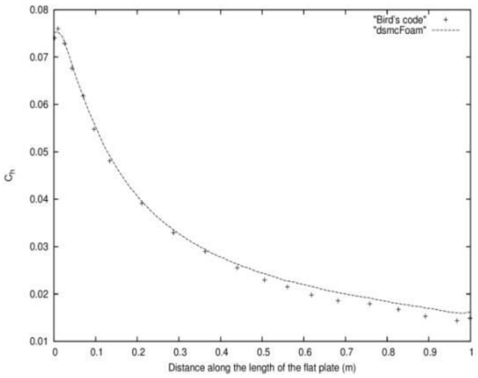


FIGURE 4. COMPARISON OF HEAT TRANSFER COEFFICIENT(Ch)

From figures 1-4 it can be seen that the results from dsmcFoam agrees well with the results of Bird[1].

3. HYPERSONIC FLOW AROUND A CYLINDER

3.1 Problem Definition

Hypersonic flow of argon gas with Mach number 10 over a 12 inch diameter cylinder is considered for the analysis. The molecular properties selected are shown in table 3.

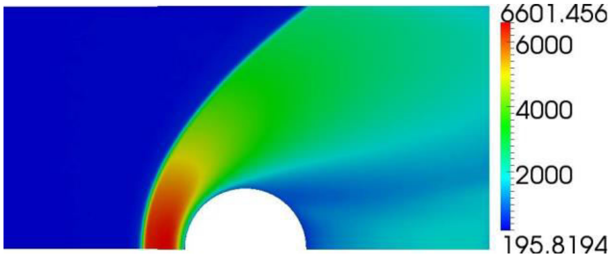
TABLE 3. MOLECULAR PROPERTIES

Tref(K)	ω	dref(m)	m(kg)
1000	0.734	$3.595\text{x } 10^{-10}$	$6.63\text{x } 10^{-26}$

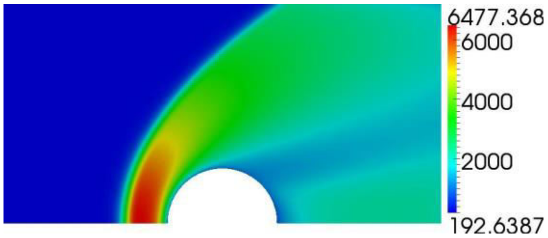
The free stream flow boundary conditions are set at left, right and top boundary of computational domain by providing free stream velocity and free stream temperature. Diffusive wall boundary condition is applied at the cylinder wall by incorporating half range Maxwellian distribution corresponding to the wall temperature and velocity. Symmetric boundary conditions are applied at the symmetric plane. The free stream velocity and temperature applied are 2624 m/s and 200 K. The temperature at the cylinder wall is considered as 500K.

4. RESULT AND DISCUSSION

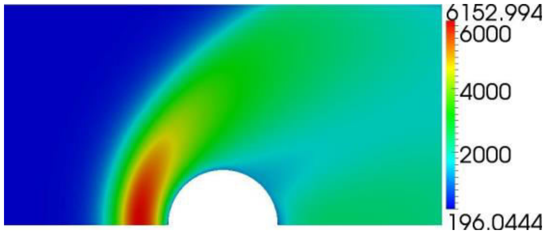
The simulation is carried out for four different Kn values such as 0.002, 0.01, 0.05 and 0.25 by changing the number densities. The figure 5 shows the temperature contours at different Knudsen numbers. It can be seen that as the Kn increases the maximum temperature decreases and shock stand off distance increases. Even though the temperature range in the flow domain is large (5000K-6500K) the cylinder wall will remains in the vicinity of 1100 K. The figure 6 shows the temperature distribution along the distance from the leading edge towards the upstream direction. The difference in the shock standoff distance is clearly visible.



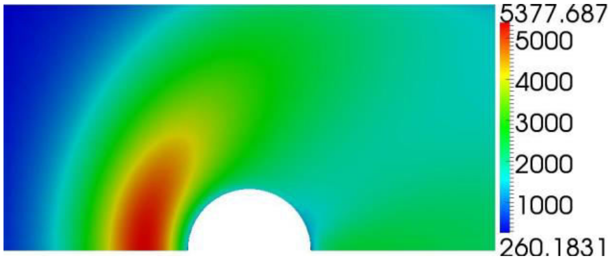
Temperature (K) for Kn = 0.002



Temperature (K) for Kn = 0.01



Temperature (K) for Kn = 0.05



Temperature (K) for Kn = 0.25

FIGURE 5. TEMPERATURE CONTOURS AROUND THE CYLINDER

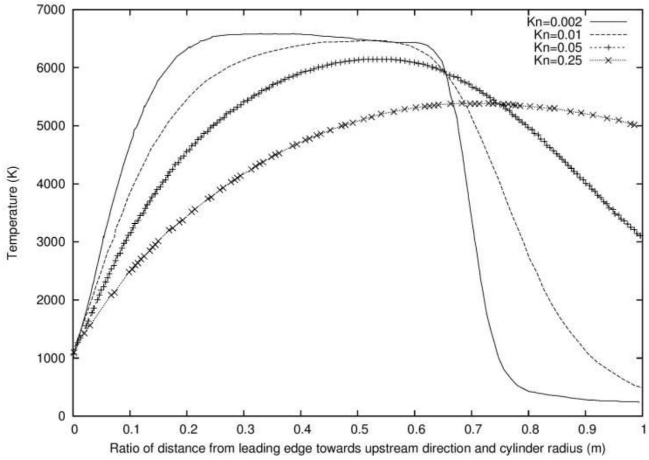


FIGURE 6. TEMPERATURE DISTRIBUSTION ALONG THE NORMALIZED DISTANCE (UPSTREAM FROM LEADING EDGE)

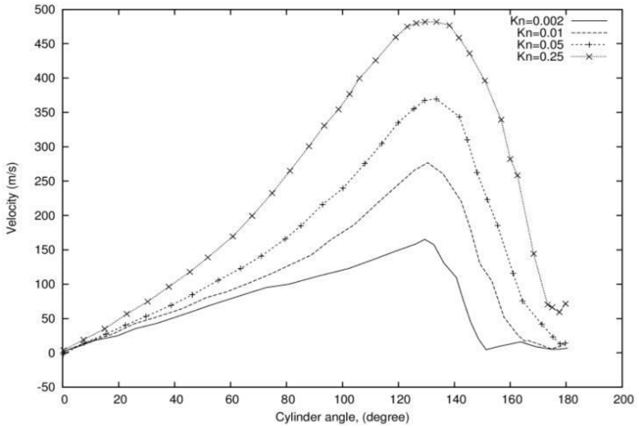


FIGURE 7. VELOCITY DISTRIBUTION OVER THE CYLINDER SURFACE

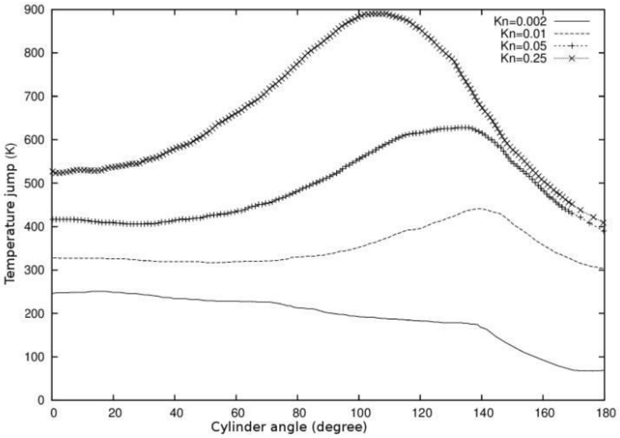


FIGURE 8. DISTRIBUTION OF TEMPERATURE JUMP OVER THE CYLINDER SURFACE

The slip velocity over the cylinder surface is shown in figure 7. It can be seen that the slip velocity increases as the cylinder angle increases due to rarefaction effect upto 130°. After 130° velocity decreases near the cylinder surface. Since the shock pattern influences the particle velocity in the wake of the cylinder. The slip reduces as the Kn decreases, even in the continuum regime (Kn=0.002) the slip occurs in the major portion of the cylinder surface. The figure 8 shows the distribution temperature jump in the cylinder surface.

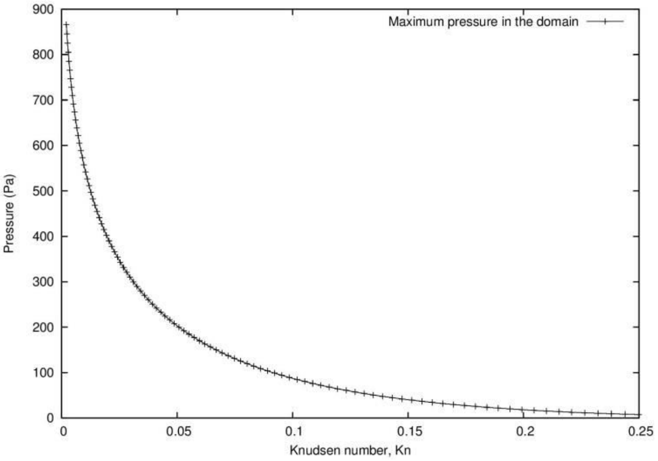


FIGURE 9. MAXIMUM PRESSURE IN THE FLOW DOMAIN FOR VARIOUS Kn.

The figure 9 shows the maximum pressure variation with Knudsen numbers. It can be seen that for higher Knudsen number (Kn>0.1) the change in maximum pressure is less compared to lower Knudson number.

5.CONCLUSION

The dsmcFoam has been applied for analyzing rarefied flows at hypersonic regime. The solver has been validated against available test case in the literature. The hypersonic flow, that may encounter in a reentry condition around a cylinder is simulated for a Mach number of 10. The temperature contours, velocity slip and temperature jump over cylinder surfaces for different Kn (0.002, 0.01, 0.05, 0.25) are presented. It is observed that the maximum surface temperature is less than the maximum domain temperature. Even in continuum regime some amount of velocity slip and temperature jump occurs.

ACKNOWLEDGEMENT

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