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Kinetic comparative study on aerodynamic characteristics of hypersonic reentry vehicle from near-continuous flow to free molecular flow

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Abstract

A scaled model of the X38-like configuration was simulated under hypersonic conditions for the direct simulation Monte Carlo method and the unified gas kinetic scheme. The inflow conditions considered several flow regimes, from the near-continuum through the slip-transitional to the free molecular regime. Flow fields and surface properties were compared in detail between these two methods. Not only the density and temperature contours distribution but also the surface pressure, heat flux, friction distribution, both kinetic methods give fairly consistent results. Aerodynamics of the model were also achieved and compared. The results provided by both methods agreed with each other very well. The effects of the Knudsen number and angle of attack were assessed. It is meaningful to carry out comparative studies and accelerate both methods to further progress.

Keywords: DSMC, UGKS, Aerodynamic, Re-entry

1 Introduction

Hypersonic vehicles are attracting worldwide attention. Their design and development require a deep understanding of hypersonic flows. Accurate prediction of hypersonic flows around re-entry vehicles remains one of the most challenging problems in aerospace engineering [1–3]. During re-entry, hypersonic vehicles will encounter different flow conditions. Generally, flows can be classified into three regions according to the Knudsen number which is defined as the ratio of the mean free path to the characterized length of the flow [4]. When the Knudsen number is small (< 0.001), the gas can be regarded as a continuum. When the Knudsen number is very large (> 10), the flow is called free-molecule flow. Between the continuum flow and the free-molecule flow is the slip-transitional flow region, where molecular transports and collisions are just as important. Rarefied gas effects are of crucial importance for aerodynamic performances of hypersonic vehicles. Very high velocity and temperature with very low density make the conditions difficult to be reproduced in ground-based experiments. Appropriate physical

model for such flows is also a difficulty since the complex physical and chemical phenomena will take place during the re-entry phase. At present stage, accurate prediction of rarefied aerodynamics has to rely on molecular kinetic methods.

Among many kinetic methods [5–10], the direct simulation Monte Carlo (DSMC) method, proposed and developed by G.A. Bird since 1960s [11], has become the standard solution tool for numerically simulating hypersonic rarefied flows. It directly simulates gas flows by tracking a representative number of simulator molecules through a computational mesh, in which molecules will collide with each other, or strike the surface according to the model used for the surface. It is based on many phenomenological approaches and is convenient and fast to be extended to solve complex flow fields such as chemical reaction flow and ionization flow.

Since 2010s, another novel kinetic method named unified gas kinetic scheme (UGKS) has been developed rapidly by Professor Xu to make an alternative choice for rarefied flows [12, 13]. UGKS is a multi-scale method with coupled particle motion and collision in its numerical flux modeling. It is built on an integral solution of the gas-kinetic model. It can cover the flow physics from the kinetic particle motion and collision to the hydrodynamic wave propagation.

Experimental data under rarefied conditions are rare and then numerical methods are hard to be verified by experiments. DSMC and UGKS solve the Boltzmann equation separately from rather different ways, so it is meaningful to conduct comparative studies and accelerate each other to further progress. Comparative studies on simple flow and geometry have been carried out generally by many researchers [8, 12, 13]. However, to the best of our knowledge, it is rare to see similar studies on practical engineering geometries in published literatures. In the present paper, DSMC and UGKS are used to numerically simulate flows over a X38-like re-entry vehicle under hypersonic rarefied conditions. Flow field results, aerodynamic forces and heat flux along the vehicle surface are compared in detail.

2 DSMC and UGKS approach

The DSMC method has been developed based on the kinetic theory, Monte Carlo method, particle dynamics, as well as statistical physics and chemistry, etc. The efficient stochastic treatment of binary intermolecular interactions makes it capable of solving rarefied gas flow problems for a much larger range of time and length scales. After half a century's development, DSMC has evolved into de facto the main tool to study complex multidimensional engineering problems in the rarefied transitional regime [14]. The DSMC has the following advantages [14]: (1) comparative simplicity of transition from one-dimension to two- and three-dimension; (2) the possibility of using various models of gas and gas-surface particle interaction; and (3) the possibility of effective application of the method on modern parallel computers. However, DSMC is still prohibitively expensive for near-continuum flows and it will suffer significant statistical errors in low speed flows [15].

Different from other kinetic approaches, the UGKS method tactfully utilizes the integral solution of the kinetic model in the flux evaluation across the cell interface. The integral solution gives accurate representations in both continuum and free molecule flows. It is very promising for multiscale unified modeling of the full Boltzmann equation and is being under rapid development. UGKS doesn't have the problem of the statistical error

and its time step is determined only by the CFL condition and not limited by the mean collision time. So, it is more efficient in flows covering various regimes especially when the local Knudsen number is low.

DSMC has been regarded as a standard tool for rarefied gas flow while UGKS is a relatively new method with many features being developed like chemical reactions, radiation and so on. More details about these two methods can be found in references [8, 11–13, 16–18].

3 Results and discussions

The current study considers a Mach 8 hypersonic flow of argon/nitrogen over a three-dimensional scaled X38-like model. The configuration of the model is illustrated in Fig. 1. It has a lift-body shape with the characteristic length and area being 0.28 m and 0.012 m² separately. Like many other re-entry vehicles, blunt body is used to generate strong shock waves and dissipate the energy to reduce the surface heat flux. The fuselage is almost a cylinder with tails up a little. Two inclined empennages are arranged on both sides at the back of fuselage. The model is a symmetry.

Flow conditions are listed in Table 1. The freestream velocity is 1115.31 m/s for argon and 1220.58 m/s for nitrogen. The freestream temperature is 56 K and the surface temperature is fixed at 300 K. The freestream density is varied such that different Knudsen numbers can be considered. The flow regimes from near-continuum to free molecule are covered. A Knudsen number of 0.00275 is considered to be near the limit of the continuum, no-slip regime. At a Knudsen number of 0.0275, the flow is well within the slip regime. A Knudsen number of 0.275 would be considered outside of the slip regime and into the transition regime. For a Knudsen number of 2.75, the flow would be considered to be free molecular. The Knudsen numbers listed in Table 1 are calculated using the hard-sphere molecular model based on freestream conditions and the characteristic length of the model. Due to the symmetry, the computations can be performed only for one half to reduce the computation time.

For all cases, six angles of attack including 0°, 10°, 20°, 30°, 40°, 50° were considered for argon and two angles of attack including 0°, 20° were considered for nitrogen in DSMC

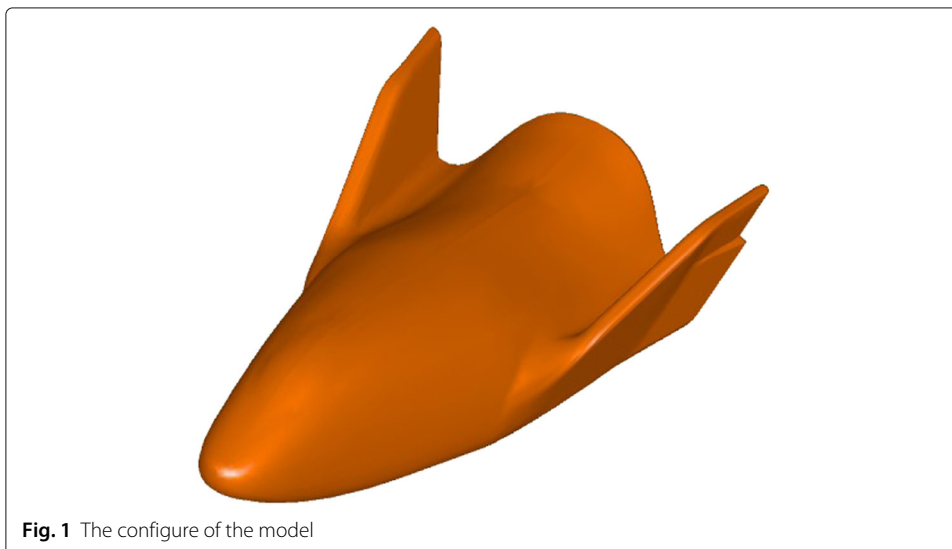


Table 1 Computational conditions

	Ma	Re	Kn _{HS}	ρ_{∞} , kg/m ³	T _∞ , K	T _w , K
Case1	8.0	5.937	2.75	1.11×10^{-7}	56	300
Case2	8.0	59.37	0.275	1.11×10^{-6}	56	300
Case3	8.0	593.7	0.0275	1.11×10^{-5}	56	300
Case4	8.0	5937.0	0.00275	1.11×10^{-4}	56	300

simulations. For case 3, six angles of attack including 5°, 10°, 20°, 30°, 40°, 50° were considered for argon in UGKS simulations. For other cases, only one angle of attack of 20° was simulated in UGKS simulations. Diatomic nitrogen was not considered in UGKS simulations.

Figure 2 shows the computational grids used by DSMC and UGKS. Unstructured grid was employed by DSMC while structured grid employed by UGKS. The cells were both refined near the model surface. No mesh adaptations were employed for both methods.

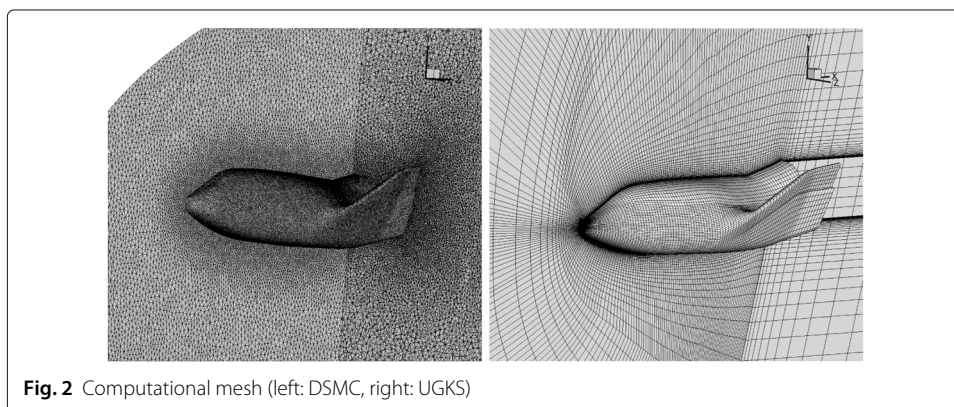
In DSMC simulations, each grid cell contained an initial 10 particles. The time step was 1.4×10^{-7} s, 1.4×10^{-7} s, 1.1×10^{-7} s and 1.9×10^{-7} s respectively for case 1 to 4. Time averaging of the instantaneous DSMC particle fields was performed after 50000 steps, and the sampling process took another 50000 steps for all cases. Weighting factors were employed with the minimum cell volume chosen as the reference volume. The surface was treated as fully diffuse and nonanalytic for all cases. The VHS model [19] was used for molecule collision with the following parameters:

$$T_{\text{ref}} = 273\text{K}, d_{\text{ref}} = 4.17 \times 10^{-10}\text{m}, \omega = 0.81(\text{argon}) \quad (1)$$

$$T_{\text{ref}} = 300\text{K}, d_{\text{ref}} = 4.07 \times 10^{-10}\text{m}, \omega = 0.75(\text{nitrogen}) \quad (2)$$

Rotational and vibrational internal degrees of freedom were included for nitrogen. The characteristic collision numbers for internal energy relaxation were assumed to be constant at values of 5 and 50 for rotation and vibration, respectively. No chemical reactions were considered.

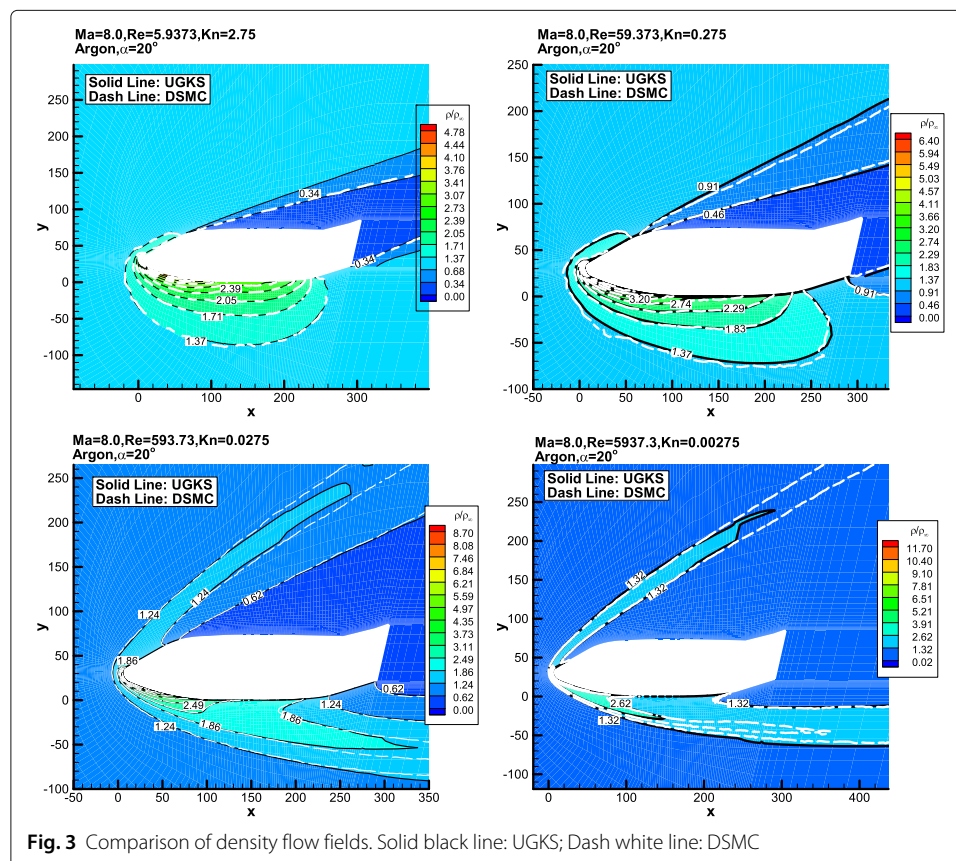
An implicit UGKS solver based on structured mesh in the physical space and equally spaced mesh in the phase space was applied. For Knudsen numbers 0.00275 and 0.0275, the meshes in the physical and phase space were 334434 and $33 \times 33 \times 33$, respectively. For more rarefied cases, a total number of 417090 cells in the physical mesh and $49 \times 49 \times 49$ phase mesh were used.

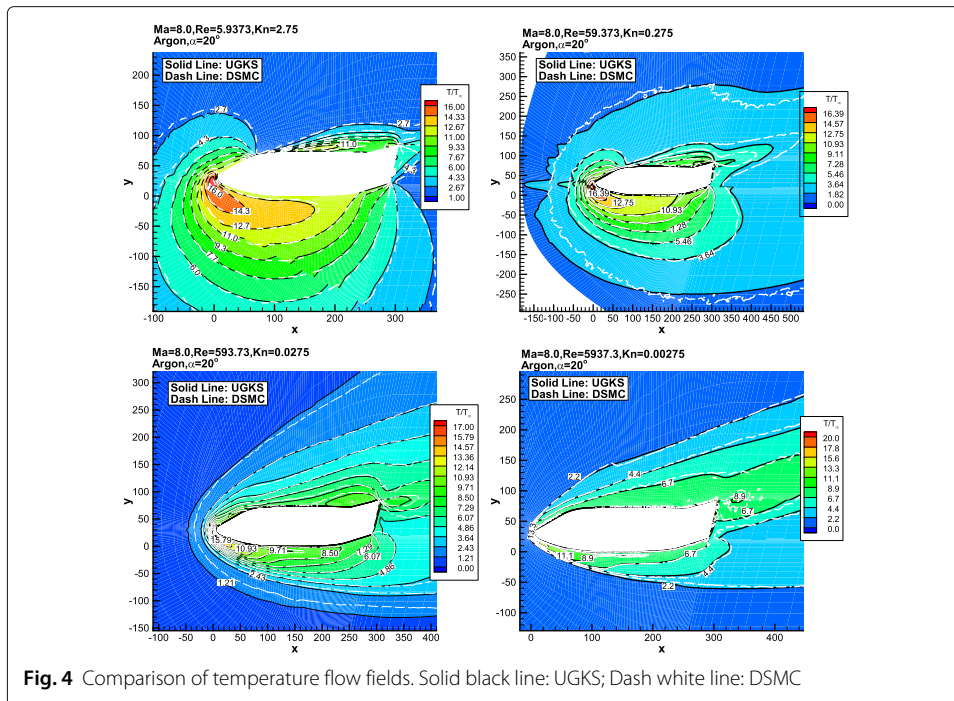


The density contour distribution which is normalized by the free stream density can be seen in Fig. 3. Working gas is argon. The angle of attack is 20 degrees. The computational mesh is large enough to capture the bow shock near the model. Overall agreements between DSMC and UGKS are excellent, with some small differences near the shock wave. As the Knudsen number increases from 0.00275 to 2.75, the bow shock in front of the model becomes much more diffuse and the maximum density ratio decreases from 11.70 to 4.78.

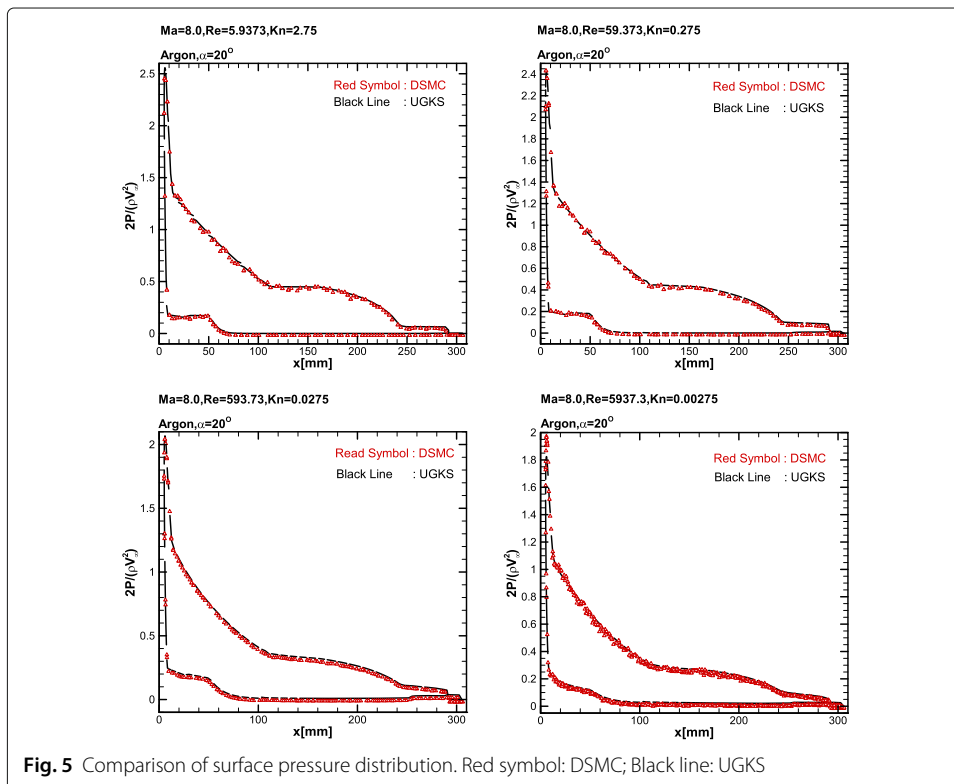
Temperature contour distributions are illustrated in Fig. 4. The $Kn = 2.75$ temperature field exhibits the typical flow features found in a hypersonic rarefied blunt body flow. A fairly thin shock wave can no longer be seen, the shock wave layer and boundary layer merge together with a very diffusive structure. Similar to the density distribution, agreements between DSMC and UGKS are also excellent, with some small differences near the shock wave. As the Knudsen number increases from 0.00275 to 2.75, the maximum temperature ratio decreases from 20.0 to 16.0.

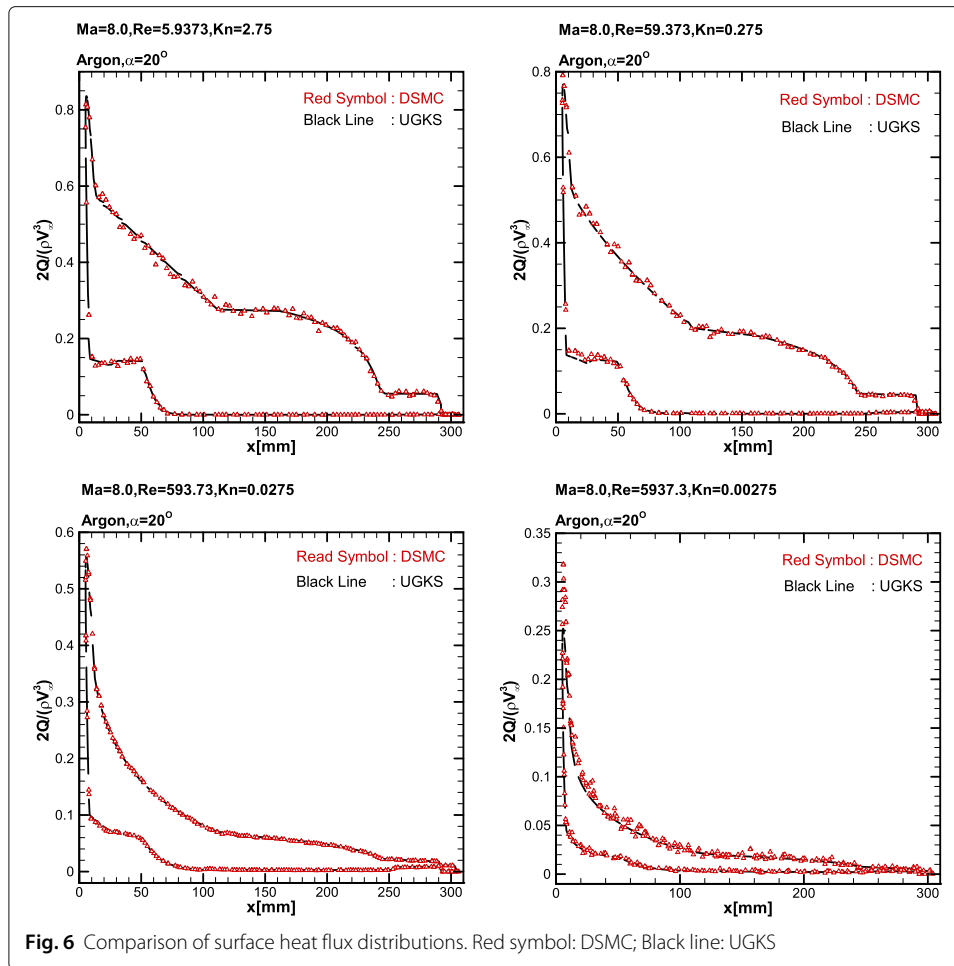
Surface quantities such as pressure, heat flux and friction on the symmetry plane of the model at the angle of attack of 20 degrees are shown by Figs. 5, 6, and 7. All quantities are non-dimensional by free stream values. Most of the high values concentrate near the model head. As the Knudsen number decreases, the maximum values and the differences between the windward side and leeward side both decrease. DSMC computations at the lower Knudsen number are difficult and the grids are not fine enough to match the requirement of the simulation merit parameter. Obvious statistical scatter can





be observed, especially for heat flux and friction. However, even with the presence of the statistical scatter, the DSMC results agree well with the UGKS results not only in terms of trend, but also in terms of magnitude. The leeward side is nearly vacuum. The pressure, heat flux and friction on most parts of this side are almost zero except a small region near the model head. The surface quantities on that region remain nearly constant because the



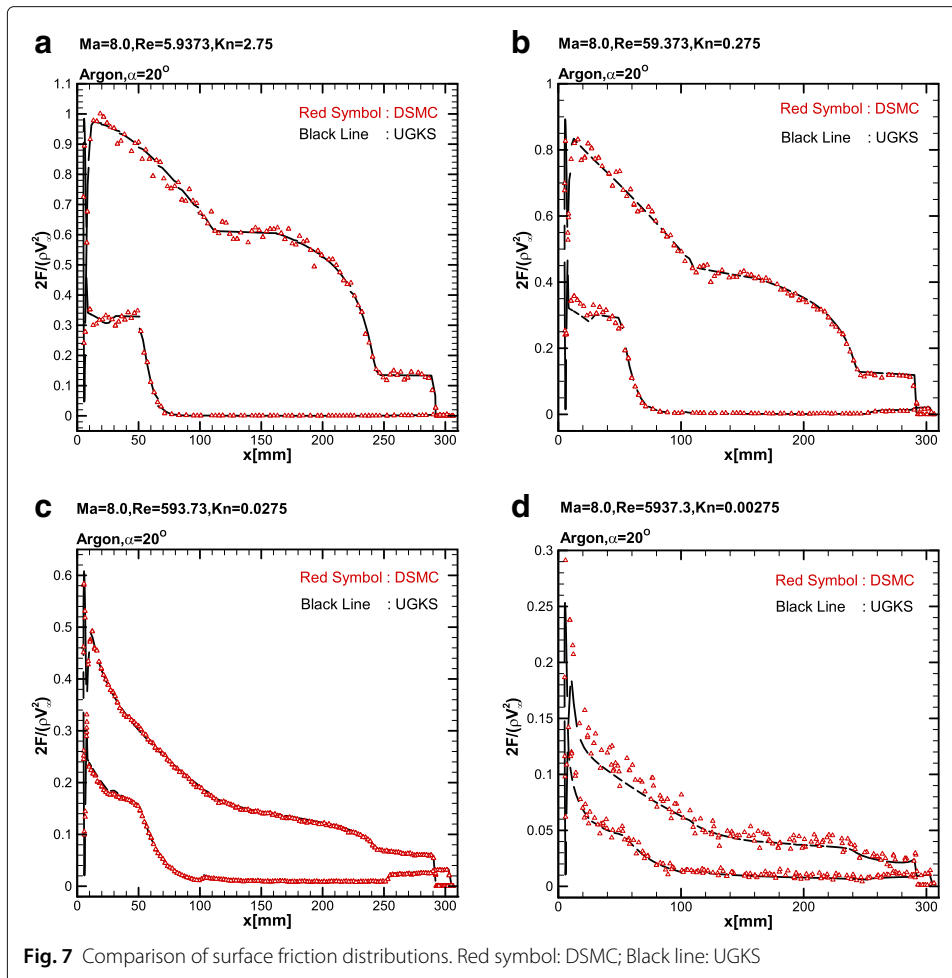


inclination is consistent with the angle of attack. The flow near this region is similar to that over a zero incidence flat plate.

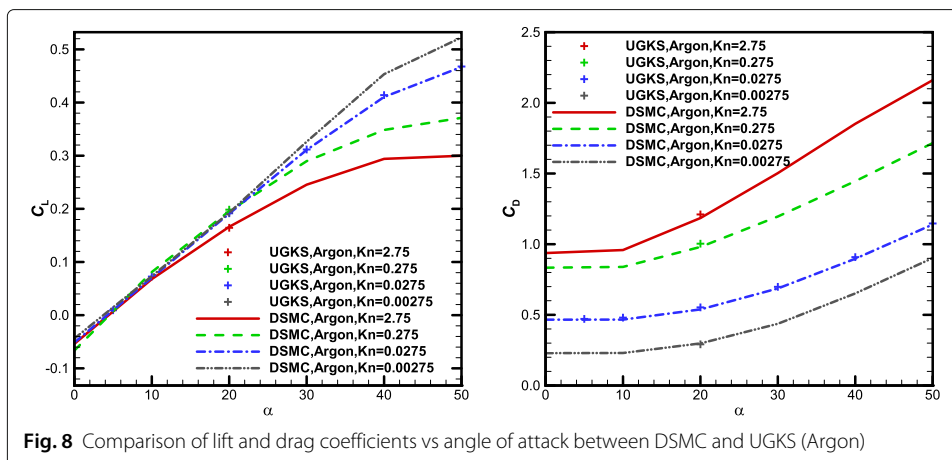
As the Knudsen number decreases from 2.75 to 0.00275, the maximum pressure coefficients decrease from 2.5 to 2.0, the maximum heat flux coefficients decrease from 0.84 to 0.32, the maximum friction coefficients decrease from 1.0 to 0.25.

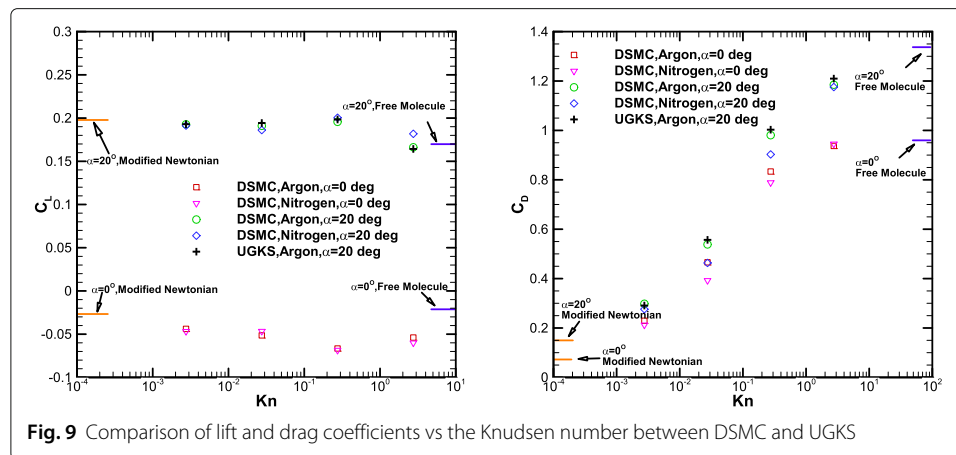
Figure 8 illustrates the variation of lift and drag coefficients against the angle of attack. As the angle of attack increases, both lift and drag coefficients increase. When the angle of attack is small, the lift coefficients at different Knudsen numbers are almost the same. However, the lift coefficient at larger Knudsen number is lower than that at smaller Knudsen number. The drag coefficient is just opposite. The rarer the flow, the greater the drag coefficient. The DSMC results agree well with the UGKS results.

Aerodynamic coefficients of lift and drag are presented in Fig. 9 as a function of the Knudsen number. The values given by the modified Newtonian and free molecular analysis for argon are also plotted in Fig. 9. They respectively predict the limit solutions for continuum and free molecular flow, which is just basically the upper and lower limits [20, 21]. The results show that the lift coefficient is not sensitive for gas components. As the Knudsen number increases, the lift coefficient doesn't change much except for $Kn=2.75$. There is an obvious decrease at $Kn=2.75$ but it is approaching the free molecular limit. The lift coefficient at the limit of free molecular flow is lower than that at the



limit of continuous flow, which is consistent with references [20, 21]. The drag coefficient increases significantly as the Knudsen number increases. The drag coefficient at the limit of free molecular flow is higher than that at the limit of continuous flow. The reason is that the modified Newtonian model neglects shear stress while the free molecular flow model neglects intermolecular collisions [21]. The DSMC results agree well with the UGKS results in all cases of Knudsen numbers.





4 Conclusion

Kinetic comparative studies on aerodynamic characteristics of hypersonic flow over an X38-like re-entry vehicle were made by using the DSMC method and the UGKS method. Simulations were made for different Knudsen number from near-continuum to free molecule. The rarefaction effects on the flow field and aerodynamic forces were assessed. Along the above-mentioned results, we can conclude that these two very different numerical methods produce similar and reasonably consistent results. Both methods have their own advantages and can promote each other's development. At the absence of experimental results, it is meaningful to carry out comparative studies and accelerate both methods to further progress.

Abbreviations

DSMC:direct simulation Monte Carlo; UGKS:unified gas kinetic scheme

Authors' contributions

The first two authors finished the numerical simulations and all authors were involved in writing the manuscript. All authors read and approved the final manuscript.

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Declarations

Availability of data and materials

All data generated or analysed during this study are included in this published article.

Competing interests

The authors declare that they have no competing interests.

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