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Rarefied Gas Numerical Wind Tunnel IV

by

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ABSTRACT

The "rarefied gas numerical wind tunnel" (RGNWT) for the simulation of rarefied gas flows around three-dimensional space vehicles is under construction. The RGNWT consists of the universal code described using the null-collision (NC) direct-simulation Monte Carlo method and the software for the grid generation and graphic display. In order to ascertain the feasibility of the RGNWT, quantitative comparisons between the NC and time-counter (TC) direct-simulation Monte Carlo methods are made for the shock wave structure and leading-edge flow.

It is shown in the leading-edge flow that the NC method is stronger to the small number of simulation molecules than the TC method; the lower limit of the number of simulation molecules for the NC method is less than one third of that for the TC method. The computation time for the NC method is comparable to that for the TC method for the same number of simulation molecules.

I. INTRODUCTION

In order to estimate the aerodynamic characteristics of three-dimensional space vehicles in rarefied gas flows, the "rarefied gas numerical wind tunnel" (RGNWT) is under construction. The RGNWT consists of the universal code described using the null-collision (NC) direct-simulation Monte Carlo method[1] and the software for the grid generation and graphic display. The aerodynamic characteristics of a whole flight body and the flowfield properties around the body are calculated and shown on a two (three)-dimensional graphic display equipment.

In order to ascertain the feasibility of the RGNWT, quantitative comparisons are being made between the RGNWT (NC) results and those obtained using the time-counter (TC) direct-simulation Monte Carlo method[2] for some basic rarefied gas flows. In this paper, the results for the shock wave structure and leading-edge flow are presented.

II. NUMERICAL WIND TUNNEL

The computation domain is taken as a rectangular solid so that the front and rear boundaries are perpendicular to the freestream flow velocity. The boundaries of the computation domain (except the rear boundary) are set far enough from the body to satisfy the freestream condition of the equilibrium Maxwellian velocity distribution. The rear boundary is set sufficiently far from the rear of the body and the streamwise gradient in the velocity distribution function of influx molecules across the boundary is assumed to be negligible. The computation domain is approximately divided into small hexahedron (pentahedron) cells, which are almost automati-

cally constructed on a graphic display equipment. The body surface is approximately divided into small trapezium (triangle) plane panels. The gas-surface interaction model is taken as the Maxwell reflection law. The surface temperature is assumed to be uniform on the whole body and constant in time. The molecular model is taken as the energy-dependent hard sphere model.[3,4] The initial velocity distribution function is taken as the free-stream Maxwellian distribution and the initial position distribution is taken as the uniform distribution with the freestream number density.

Figures 1 and 2 present typical results obtained by the RGNWT and displayed on a three- dimensional graphic display equipment. Figure 1 shows the molecular positions around the Shuttle-like space plane with the cold and diffuse reflection wall at the attack angle 30° in the rarefied gas flow of the Knudsen number $Kn_\infty = 1$ and the speed ratio $S_\infty = 10$. The freestream and body reflected molecules and molecules which collided with the body reflected ones are distinguished by colors. Figure 2 shows the energy transfer rate to the body surface panels indicated by colors.

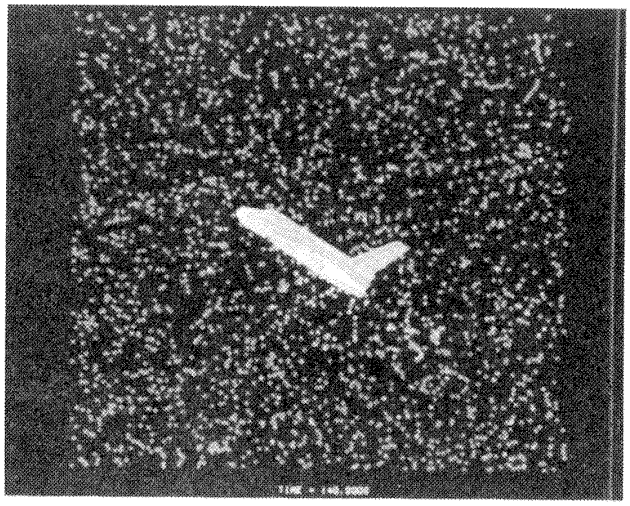

Fig. 1 Display of molecular positions around Shuttle-like plane.

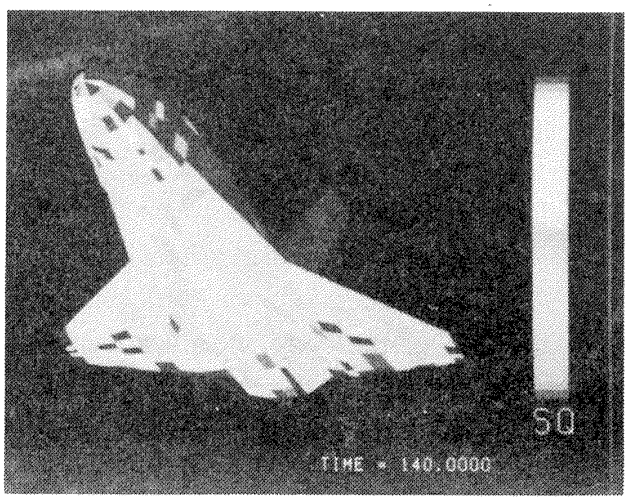

Fig. 2 Display of energy transfer rate to Shuttle-like plane.

III. COMPARISON BETWEEN NC AND TC METHODS

A. Shock Wave Structure

The number density profile, $(n-n_1)/(n_2-n_1)$, of the shock wave for the Mach number $M_1 = 8$ is compared in Fig. 3 among the NC and previous TC[5] results for hard sphere molecules and the Monte Carlo result obtained by Yen and Ng[6] using Nordsieck's Monte Carlo method (NMC), where the subscripts $_1$ and $_2$ denote the upstream and downstream values, respectively, and x is the streamwise distance normalized by the upstream mean free path λ_1. The result obtained using the TC code which was made in the same way as the Appendix G of Ref. 2 is also presented for comparison. The NC and present TC results are in good agreement but indicate a larger curvature in the upstream half of the shock wave than the previous TC and NMC profiles and are closer to

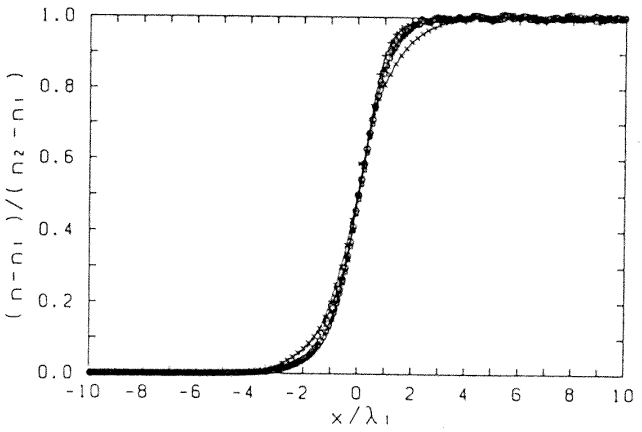

Fig. 3 Comparison of number density profile of shock wave; ○, NC; □, TC (present); ×, TC (Ref. 5); +, NMC (Ref. 6).

the NMC one than to the previous TC one in the downstream half. Because the NC and present TC results are obtained for the average number of simulation molecules per cell which is much larger than the lower limit value (which will be evaluated in the leading-edge flow), the discrepancy may be due to some numerical errors in the previous TC (and NMC) results.

B. Leading-Edge Flow

The plate pressure distribution, p/p_{fm}, normalized by the free molecule value over the sharp flat plate with the finite length $L/\lambda_\infty = 44$ and the diffuse reflection surface at the wall temperature $T_W = 0.08T_0$ for the freestream Mach number $M_\infty = 12.9$ is compared in Fig. 4 among the NC and present and previous TC results[7] for hard sphere molecules, where T_0 is the freestream total temperature and x is the streamwise distance from the leading edge normalized by the freestream mean free path λ_∞. The NC and present TC results obtained for the initial number of simulation molecules $N_0 = 7 \times 10^5$ are in good agreement but in considerable disagreement with the previous TC result. Because the convergence of the NC and present TC results by the decrease in the time step and cell size and the increase in the number of simulation molecules (see Figs. 5 and 6) are carefully checked, the possible source of the discrepancy is the insufficient number of simulation molecules (less than the lower limit) or convergence in the previous TC results.

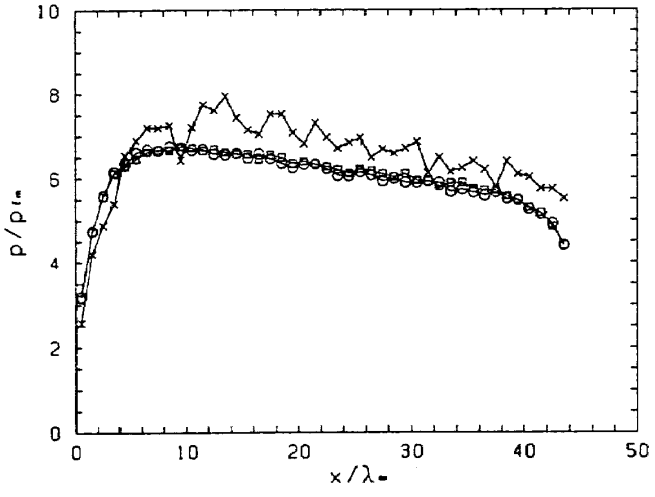

Fig. 4 Comparison of plate pressure distribution; ○, NC; □, TC (present); ×, TC (Ref. 7).

The dependence of the NC and present TC results on the initial number of simulation molecules N_0 is shown in Figs. 5 and 6, respectively. It is indicated that the lower limit of N_0 is about 10^5 and 3×10^5 for the NC and TC methods, respectively; the lower limit of the average num-

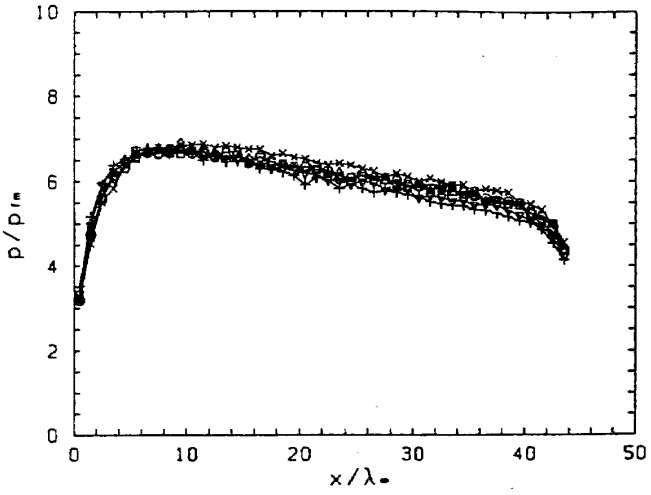

Fig. 5 Dependence of plate pressure distribution on the number of simulation molecule for the NC method; ○, $N_0 = 7 \times 10^5$; □, $N_0 = 5 \times 10^5$; △, $N_0 = 3 \times 10^5$; ▽, $N_0 = 10^5$; +, $N_0 = 5 \times 10^4$; ×, $N_0 = 10^4$.

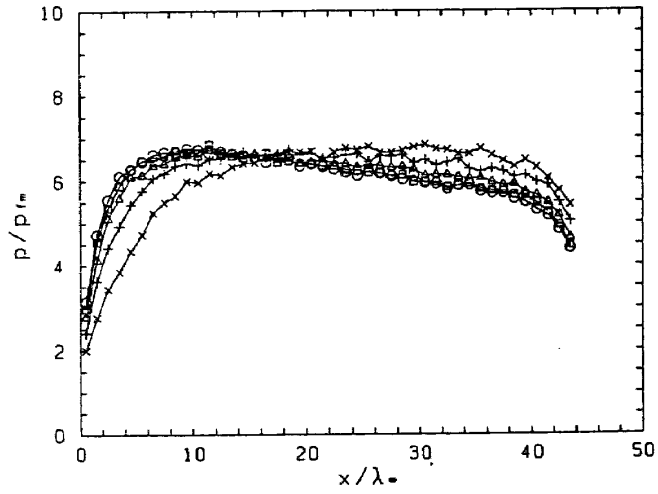

Fig. 6 Dependence of plate pressure distribution on the number of simulation molecule for the TC method; ○, $N_0 = 7 \times 10^5$; □, $N_0 = 5 \times 10^5$; △, $N_0 = 3 \times 10^5$; +, $N_0 = 2 \times 10^5$; ×, $N_0 = 10^5$.

ber of simulation molecules per cell is evaluated to be about 5 and 15 for the NC and TC methods, respectively. The fact that the lower limit of the number of simulation molecules for the NC method is less than one third of that for the TC method indicates that the NC method is stronger to the small number of simulation molecules than the TC method because of the accurate NC evaluation of the number of molecular collisions. It is noted that the computation time for the NC method is only about 10–15% larger than that for the TC method for the same number of simulation molecules.

IV. CONCLUDING REMARKS

In order to ascertain the feasibility of the RGNWT described using the NC method, quantitative comparisons with the previous Monte Carlo results obtained using the TC method are made for the shock wave structure and leading-edge flow and a considerable discrepancy is revealed. The possible source of the discrepancy is the insufficient number of simulation molecules (less than the lower limit) or convergence in the previous TC results. It is shown in the leading-edge flow that the NC method is stronger to the small number of simulation molecules than the TC method and the computation time for the NC method is comparable to that for the TC method for the same number of simulation molecules. Therefore, it may be claimed that the NC method is more feasible than the TC method especially in the simulation of three-dimensional rarefied gas flows.

The RGNWT may have a lower limit of the Knudsen number because of the limitation of the computation time and memory capacity. In order to reduce the lower limit, the acceleration of the RGNWT code on a super computer by the vectorization is in progress. The extension of the RGNWT code to gas mixtures with internal degrees of freedom, chemical reactions, and interactions with radiation is a subject of future work.

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