CHAPTER 6

CONCLUSION AND FUTURE WORK

Numerical simulations of a hypersonic flow over spiked blunt bodies with single, double and treble aerodisk of hemispherical, flat triangular and flat shape were carried out using a commercially available finite volume code for a Mach number of 6.2. Out the multiple aerodisks, the radius of the front disk is varied from 2 *mm* to 8 *mm* for single aerodisk, from 2 *mm* to 6 *mm* for the two disk aerospike and from 2 *mm* to 4 *mm* for the three disk aerospikes. For any multiple aerodisk spiked configuration the front disk is the smallest and the size of disks increases progressively for second and third disks. Typical progression of disk size chosen are 2-4, 4-6, 6-8 *mm* for two disk configurations and 2-4-6 and 4-6-8 *mm* for three disk aerospikes. The overall l/D ratio of these aerospikes is varied from 1 to 2.5 and for any l/D ratio the intermediate position of the rear aerodisk l_1/l is selected to be 0.25, 0.5 or 0.75. Similarly the relative position of the mid disk, for treble disk is chosen to be 0.25, 0.5 or 0.75 of the total distance between the rear and the front aerodisk.

The effect of single disk aerospike is well established for drag reduction. For single hemispherical aerodisk spiked configurations, the highest reductions in drag are obtained with 6 *mm* disks which offer reductions of about 60% at l/D=1 to 67% at l/D=2.5. The reductions become more favorable for the flat aerodisks which give best results for a disk size of 6 *mm*. For this size of the flat aerodisk, the spiked configuration gives a reduction of 57% at l/D=1 and of 70% at l/D =2.5. The single flat triangular aerodisks give the most favorable reductions for a disk size of 4 *mm* with 57% reduction at l/D=1 to 70% reduction at l/D=2.5. The magnitude of aerodynamic heating depends highly on the freestream turbulence levels. Under the ambit of assumptions and model of turbulence used in this research, the single disk aerospike gave a reduction in peak reattachment heat fluxes and also in total heat transfer rates to the main body, except for cases with front disk radius of 2 *mm*. With single aerodisk of radius 6 *mm*, reductions of about 45% in peak reattachment heat flux is obtained at *l/D*=2.5 which goes up to 60% for flat triangular aerodisk and 61% for flat aerodisk.

The use of multidisk aerospike strengthens the reductions in drag and aerodynamic heating. For a given *l/D* ratio, the increase in radius of the aerodisk reduced both aerodynamic heating and drag. With the increasing length, a further reduction in both aerodynamic heating and drag is observed. Both the aerodynamic drag and heating are also highly dependent on the position of the intermediate aerodisk as well, for two and three aerodisk spikes. As far as the shape of aerodisk is concerned, for similar configurations, the flat triangular aerodisks were observed provide a higher drag reduction as compared to the hemispherical and flat disk aerodisks.

The trends for heat reductions are also similar. The drag reductions in flat aerodisk are considerably higher as compared hemispherical aerodisk with reductions of about 40% to 78% is observed as compared 24% to 66% for the hemispherical aerodisks. The drag reductions for the flat triangular aerodisks are similar to that for the flat aerodisk owing to similar flowfield structures. For the double disk aerospikes also the largest reductions in drag are observed at the highest *l/D* ratio investigated i.e. 2.5. The drag reduction for the two and three disk aerospikes improves with the forward movement of the intermediate aerodisks as they increase the area of recirculating region of flow between the aerodisks which produces suction in forward direction. But for few cases with rear disk size of 6 *mm* or 8 *mm*, positioned at very forward positions with combination both large *l/D* and l1/l, the high drag on the rear aerodisk neutralizes the reductions for the main body. The drag hence, ceases to reduce with increase in l_1/l ratio for these cases. The reductions in peak reattachment heat fluxes and the total heat transfer rates also follow the same suit as for the drag reduction.

The hemispherical double disk aerospike offers up to 65 % reduction in peak heat fluxes at *l/D* of 2.5 with rear disk at 0.75 of the total length of spike. For flat aerodisks, these reductions go up to 68% with the rear aerodisk at l_1/l=0.5 for a 6-8 *mm* size. Any further forward movement of the rear flat disk with r1=6 *mm* and r2 = *8 mm* to l_1/l=0.75, offers no further reduction in heat fluxes. In fact the reductions are diminished slightly at l_1/l=0.75 as compared to l_1/l=0.75 at almost *l/D* ratios. Both for the drag reduction and the reductions in local heat fluxes and the total heat transfer rates the three disk aerospike performs better than a two and single disk aerospike. At *l/D* ratio of 2.5, the 4 *mm* single hemispherical aerodisk offers about 62% reduction in drag while the two disk aerospikes offer 68% and 70% reductions at l_1/l=0.5 and 0.75 respectively. The three disk configurations offer a still higher reduction between 73% and 74% in aerodynamic drag. For flat aerodisks also the effect of multiple aerodisk on drag reductions are similar. The single flat aerodisk of size 4 *mm* gives a reduction of 65% in drag at *l/D*=1.5 while the two flat disk aerospikes with same size of the front aerodisk and *l/D* ratio give better reductions of about 69% to 70%. For three flat aerodisks, these reductions scale up marginally to 72%. At a higher *l/D* ratio of 2.5, the maximum reductions given by flat aerodisk of radius 4 *mm* is 70% for single aerodisk, 74% for double aerodisk and 77% for treble aerodisks.

The trends in reduction of heat transfer rates are also similar to drag reductions. At the highest *l/D* ratio of 2.5, the reduction of 21% with single hemispherical disk of radius 4 *mm* improves to 33% with two aerodisks and to 50% with three hemispherical aerodisks with the same radius of the front aerodisk. The flat aerodisks are much superior in reducing the reattachment heat flux to the main body. A single flat aerodisk of radius 4 *mm* gives a reduction of 39% at an *l/D* ratio of 1.5. At the same *l/D* ratio and radius of the front aerodisk, the spiked configurations with two flat aerodisks give reductions of about 48% which further improves to 54% for three aerodisks. For an *l/D* ratio of 2.5 a single flat aerodisk of radius 4 *mm* gives a reduction of 47% in peak reattachment heat fluxes which increases to 54% for two disks and goes up to 63% for the three flat disk configurations.

As far as the reductions total heat transfer rates are concerned, at *l/D*=2.5, the hemispherical aerodisks offer reductions of up to 8% with single aerodisk, 19% with double disks and 27% for the three aerodisk configurations. The reductions in total heat transfer rates to the main body are emphasized further for the flat aerodisk spiked configurations. For flat aerodisk spiked configurations with same front disk radius of 4 *mm* the reductions up to 27% with single disk, up to 34% with double disks and up to 39% with treble disk are obtained.

The use of multiple aerodisk aerospikes at the nose of a blunt body certainly seems to be advantageous for the purpose of reduction of aerodynamic drag and heating at hypersonic speed. It is observed in the ambit of current research that two aerodisk configurations outperform single aerodisk configuration in terms of heat and drag reductions. The three aerodisk configurations however yield only a marginal reduction in aerodynamic drag over the two disk configurations. For reduction of heat fluxes and heat transfer rates though, the three disk configurations are extremely advantageous and give much larger reductions are compared to the two disk configurations. All the reductions provided by the multiple aerodisk configurations improve with increasing radii of the aerodisks except for very long aerospikes with a large disk sizes have diminished drag reductions. Among the shapes of disks investigated, the flat aerodisks are much superior to the hemispherical aerodisk in terms of both drag reduction and the reduction of local and total heat transfer rates to the main body but are associated with a very large local heat fluxes at the sharp edges of the disks. The flat triangular aerodisks performs almost same as the flat aerodisks with added advantage of not so high local heat fluxes at the aerodisks itself.

For hypersonic vehicles, the use of multidisk aerospikes is an effective passive means to alleviate both the aerodynamic drag and peak heat transfer rates to a blunt body simultaneously. Among the configurations investigated the best drag reduction results were obtained for l/D=2.5, l1/l=0.5 and l_2/l'=0.5 for the three disk aerospikes of size of r_1, r_2, r_3=8, 6, *4 mm* radii. For these geometric parameters the hemispherical, flat and flat triangular aerodisks gave reductions in drag of 74%, 77% and 76% respectively. Even for the purpose of reduction of aerodynamic heating of the main body, the treble disk configurations with aerodisk size r_1, r_2, r_3=8, 6, *4 mm* and geometric parameters of l/D=2.5, l_1/l=0.5 and l_2/l'=0.5, proves to be very fruitful configuration irrespective of the disk shape. For the above geometric parameters, the hemispherical aerodisks offered a reduction of 50% in reattachment heat fluxes and 27% in total heat transfer rates while the flat and flat triangular aerodisks gave reductions of 63% and 62% in reattachment heat fluxes respectively. The respective reductions in total heat transfer rates for treble flat and flat triangular aerodisks were found to be 39% and 38%. But the best reduction in peak heat fluxes and total heat transfer rate to the main body is offered by the two disk configurations with disk size of r1=6 *mm* and r2=8 *mm*, primarily because of the large size of the aerodisks at fairly forward positions, onto which a large amount of heat is dissipated by the flow before reaching the main body. The reductions for these configurations are 57%, 68% and 68% in peak reattachment heat fluxes respectively for the hemispherical disks, flat aerodisks and flat triangular aerodisks. The reductions in total heat transfer rates to the main body for these double disk configurations are respectively 56%, 45% and 48% for the hemispherical, flat and flat triangular aerodisks. Nevertheless, in authors opinion the three disk configurations with disk size of r_1, r_2, r_3=8, 6, *4 mm* with l/D=2.5 and l_1/l=0.5 and l_2/l'=0.5 are the optimal configurations that reduce both aerodynamic drag and heating tremendously.

The author is also of the opinion that for both for the reduction of aerodynamic heating and the reductions of aerodynamic drag, longest aerospikes with largest possible radius should be used, subject to structural constraints. Thus multidisk aerospikes should certainly be considered as a means of drag and heat reduction and further elaborate research must be conducted experimentally so as to implement these designs for future hypersonic vehicles. The specific research tasks that need to be undertaken as future work for the integration of multidisk aerospikes onto future hypersonic vehicles can be listed as follows.

(a)All the investigations in the current research have been carried out with assumptions of axisymmetric flows. The more general flows are not axisymmetric and hence a full three dimensional study of the flow around various spiked configurations at various angles of attacks to ascertain the reductions in aerodynamic heating and drag at non-zero angles of attack.

(b) The existence of multiple recirculation zones ahead of the blunt body can make the flow more stable and effect the oscillation of the shock wave in an unsteady flow situation. The effects of multiple recirculation zones on the stability of the flow and shock wave oscillations at various Mach numbers must be studied.

(c)At hypersonic speeds, the structural load on the spike and the aerodisks are tremendous. Also the heat fluxes to the aerodisks are severe as compared to the main body. The structural and the thermal load can produce signification distortions to the geometry of the aerospikes and can cause ablation or fusion of the aerodisk material. Thus the effect of all these parameters must be integrated through a coupled aero-thermo-structural analysis of the spiked blunt bodies with multiple aerodisks.

(d)The results in the current research are obtained through the numerical solution of the Reynold averaged Navier-Stokes equations with high levels of uncertainty in the approximation of turbulent stresses. The findings of the current research hence must be validated through direct numerical simulations, if feasible, or through experiments.