CHAPTER 2

LITERATURE REVIEW

Literature review provides a panoramic journey from yesterday's challenges through today's most important advances in research and development. It also presents concepts, methods of analysis, technical knowledge, exploratory developments, and new applications. Right on the onset of cold war, United States started research for the design of ballistic missiles in 1950s. The missiles developed in earlier periods featured pointed nose on a slender body, which has traditionally low wave drag while entering Earth's atmosphere at high speed but also had extreme temperature at the nose cone due to attached. A study on the ballistic missiles entering the earth's atmosphere at high supersonic speed was first done by **H. Julian Allen and A.J Eggers, Jr** [10] in 1953. They made a significant contribution to hypersonic aerodynamics by proposing the use of blunt nose for re-entry vehicles and established that although a blunt body offers a high pressure drag, it has a detached shockwave which minimizes heat transfer to the vehicle as compared to a slender body with attached shock wave. Allen and Eggers obtained an expression for heat transfer rate to a blunt body, and proposed that the stagnation point heat transfer rate is inversely proportional to the square root of the leading edge radius of the blunt body.

In comparison to a slender body design, the blunt body produces more drag; hence slender bodies are preferred over blunt bodies, keeping aerodynamic drag as a main parameter. It has been established that although pointed bodies generates less drag, the amount of aerodynamic heat produced is tremendously high and it varies with the cube of the freestream velocity. Therefore for high speed flow slender bodies are not utilized, as a huge thermal gradient can lead to the failure of the sensitive electronic equipment employed in the vehicle. These thermal gradients can also lead to the ablation of the material used for the structure which can cause undesirable aerodynamic performance and may even cause disintegration of the vehicle itself [1].

The severe increase in pressure drag for blunt is caused by the detached shock which is formed just ahead of the nose and can be reduced by changing the flowfield ahead of stagnation region. One such mechanism to do this is the use of an aerospike or an aerodisk. An aerospike replaces a strong bow shock with a series of oblique shock and promotes the separation of flow and creates shear layer. This shear layer is propagated in the flow direction and reattaches at forebody to form a zone of recirculating flow. There is a high local heat flux and pressure across the zones where reattachment occurs, but owing to the reattachment zone, the pressure and heat flux decrease ahead of the blunt nose. The effectiveness of the aerospike is further increased by introducing a blunt face aerospike known as aerodisk and sizable research is oriented towards the findings of aerospike and aerodisk shapes and sizes.

Alexander SR [11] in 1947 at the Langley Pilotless Research Division carried out numerous firing tests on blunt and slender nosed bodies at various Mach number ranging from 0.95 to 1.37. He proposed that mounting a cylindrical thin rod with large conical tip on blunt forebody may alter the fineness ratio and effect of increase in weight. It was also observed that although there was a small drop in the drag of the bodies using windshield but it was still more than that of the pointed forebody at Mach number 1.37.

Mair W.A [12] in 1952 did a comprehensive study on spiked blunt bodies which is considered as a landmark study in this field. He did experimental investigation of the flowfield around spiked blunt body for hemispherical and flat cylindrical models at a freestream Mach number of 1.96 and Reynolds number of 1.65×10^{5}. He experimentally observed the flowfield around spiked hemispherical and flat cylindrical bodies in relation to the effect of spike length. Mair was the first one to observe the flow instability around spiked blunt bodies. He also observed that shock wave at the probe tip changed its shape in a self-sustained manner for a certain range of its length. He observed that the flow oscillation with respect to pressure variance between the flow inside the recirculation zone and the aft of the reattachment shock was substantial for certain range of probe length on a cylindrical model.

Jones J. J. [13] in 1952 did another investigation for flow around a hemispherical nose with pointed rod protruding from the nose at Mach number 2.72. The length of the protruding rod varied from 1 to 6 times the radius of the hemispherical cylinder. Jones pointed out that there exist only one streamline that stagnate on the reattachment point of the forebody surface, and this streamline divided the flow between the recirculating zone and the non-circulating main flow.

Piland and Putland in 1954 [14] introduced the term “spike” to the protruding rod at the nose of a blunt body while investigating hemispherical nose with and without pointed spike of different lengths. The study mainly focused into the effect of spike at low Mach numbers from 0.7 to 1.3 and Reynolds number varying from 1.44×10^5 to 2.64×10^5. They found that for a given Mach number, no variation in drag is achieved irrespective of the spike length.

Stalder and Nielsen in 1954 [15] studied the aerodynamic and thermal effects, collectively known as aerothermodynamics of aerospikes. They examined temperature variation on a hemispherical cylinder for Mach number up to 5.04 and Reynold number ranges from 1.55×10^5 to 9.85×10^5. The hemispherical cylindrical model studied by Stalder and Nielson was fitted with different spike tips of different shapes such as pointed tips, conical and flat aerodisk. With varying *l/D* ratio between 0.5 and 2, it was observed that irrespective of the length of spike and the tip geometry, the rate of heat transfer to the spiked model was twice that of the non-spiked model. This study is considered as first study in the area of aerothermodynamics of aerospike They justified that the increase in the rate of heat transfer was because of the impingement of the of turbulence shear layer on the surface of the model and the raised turbulence level in the dead region of air.

In 1955 **Jones J.J** [16] did a series of wind tunnel test to study the drag reduction for a hemispherical model by mounting a rod ahead of the nose at a Mach number of 2.72 and Reynold number of 1.83×10^6. The geometric parameters which were considered for drag reduction were base geometry diameter, rod length and windshield geometry. The length of the rod was varied between 0.415, 1.125 and 1.464 times the nose diameter of the model. It was observed that drag reduction depends on geometry of both windshield and rod length. The increase in the drag was observed for an excessive longer rod length as the flow first reattaches to the rod behind the windshield and then again separates from the rod ahead of the base body. Reductions in the drag was observed for all windshield geometries where the flow is detached at the rear of the windshield and remain separated for the entire rod length and reattaches near the rim of the base body.

Beastall D and Turner J. in 1957 [17] did investigation on flat cylindrical model for a freestream Mach numbers of 1.5, 1.6 and 1.8 with Reynolds number of 1.125×10^6. The model consists of a pointed ogive tip aerospike with conical aerodisks of variable vertex angle and the *l/D* ratios of the spikes investigated were varied up to 4.7. A new type of unsteadiness in the flow was observed for a spike of longer length and the drag on specific spike length was found to depend upon whether the spike was retracted or extended.

Bogdonoff S M and Vas I E in 1959 [18] did a preliminary study on the effect of aerospike on the aerodynamic drag and heat transfer to a blunt body. Investigations were carried out on two models namely hemispherical cylinder and flat cylindrical model at Mach number 14 and Reynold number 3.6×10^5 to study the effect on heat transfer rate and pressure distribution around spiked bodies. They observed a reduction in the heat transfer rate for spiked model that was because of the reason that the separated shear layer remained laminar up to reattachment. Both these models viz. the flat hemispherical cylinder and hemispherical cylinder recorded unsteadiness in the flow at Mach number 14.

Crawford [19] in 1959 carried out a breakthrough experiments in this field. He investigated the effect of flowfield over a spiked blunt body for a freestream Mach number of 6.8. A detailed study of the effect of Reynolds number and shape of the geometry on pressure distribution, aerodynamic heating and nature of flow in the vicinity of surface were studied experimentally. The Reynold number was varied from 0.12×10^6 to 1.5×10^6 based on the model diameter and freestream conditions. It was observed that increasing the spike length results in reduction of drag and heat fluxes but the reduction in the drag is not felt if the *l/D* ratio is increased beyond 4. He observed that the peak value of the surface pressure and heat flux are associated with the point of reattachment of the shear layer. He also observed that the heat flux varies from half to double at the stagnation point of the non-spiked model for various spike lengths whereas peak pressure remains below the stagnation pressure for all spike length.

In relation to the changes in flow pattern due to addition of aerospikes, **Chapman et al. [20]** in 1957 studied the change of flow pattern for separated flow at subsonic and supersonic speeds. The transition effects of stresses were monitored by them. They were the first to introduce the word "dividing streamline" which is related to separation and reattachment point of shear layer in equilibrium flow. The effect of distance from separation point on the thickness of shear layer was also observed. They defined the dividing streamline as separation point and reattachment point of shear layer for steady flow which links the separation and stagnation reattachment points at equilibrium.

Wood C J [21] in 1961 did the comprehensive study of hypersonic flow around a spiked cone to study the fluctuating structure of the flow pattern. He changed both base geometry and the spike length in order to understand the flowfield structure for freestream Mach number of 10 and Reynold number 0.5×10^5. Wood classified the flow patterns around spiked blunt bodies into five categories for a cone-cylindrical model with varying semi apex angle of 30º to 180º. The "dividing streamline" concept which was introduced by Chapman [20] was first used by wood for his experiment. This was referred to be the linking streamline at steady flow conditions of the separation and the reattachment points of the shear layer.

Wagner R D and Pine C P in 1961 [22] did an experimental investigation to analyse the pressure distribution and heat transfer rate for a series of re-entry nose shapes at Mach number of 19.4 and Reynold number 0.3×10^6. It was found that the pressure distributions on the nose shapes investigated were well predicted by the Newtonian, Prandtl-Meyer shock expansion theory and the conical flow theory, except near the nose where boundary layer bleed off effects seemed to be present. The results obtained by Wagner R and Pine CP of spiked blunt bodies were also compared with the earlier experimental data for heat transfer and pressure distribution and found to be in close agreement. The heat transfer rate on blunt bodies as predicted by the Lees [5] showed a good agreement with the data obtained in reference [22]. He also concluded that blunt bodies yield lower heating levels with respect to the pointed counterpart because of redistribution of aero heating over a pretty larger area particularly at the stagnation point.

Holden M [23] in 1966 did another significant experiment where he studied the effect of heat transfer and the effect of separated flows over spike d bodies for a freestream Mach numbers of 10 and 15, and a Reynolds number 0.27×10^6.Three different configurations were investigated viz. a flat cylinder, a conical cylinder and a hemispherical cylinder. The geometry of the conical nose was varied by taking different semi vertex-angles of 30º, 40º, 60º and 75º while the length of the pointed spike was varied by up to 4 times the diameter of the base geometry. Holden classified the flow patterns around spiked blunt bodies and extended the classification by wood [18] for the conical cylinder models to more refined flow patterns at higher values of Reynolds number and Mach number. Holden revealed that the maximum value of the local heat transfer rate at the point of reattachment is related to the reattachment angle. The reattachment angle depends upon both the length of the spike as well as the vertex angle of the cone.

McGhee and Staylor in 1969 [24] investigated the effect of a sharp pointed spike for a freestream Mach numbers of 3, 4 and 6 and freestream Reynolds numbers of 1.83×10^6. Two conical models were investigated with vertex angle of 120º with a bluntness ratio of 0.50 and 0.25. The bluntness ratio is defined as the cone nose diameter to the cone base diameter. The base diameter of the investigated cone was 11.43 cm while the length of the spike varied from 0.055 to 0.083 times the base diameter. Two different spike diameter of 0.044 and 0.011 times the cone base diameter were used in the investigation. These models were studied at 0º, 2º and 5º angles of attack. The flow features of short spikes for various ratios of the length of the spike to bow shock standoff distance ahead of the model were compared with that of blunt body without spike. The effect of spike length on pressure distribution was found to be predominant as compared to the tip angle and spike diameter. It was also found that the flow at spike tip was attached and steady with slight increase of less than 1% in drag for the body.

The investigations by McGhee and Staylor were further expanded by **Staylor** in 1970 [25] to a freestream Mach number 9.6 and Reynold number ranging from 6×10^4 to 23×10^6. The investigations confirmed that the flow phenomenon formed by the aerospikes were a function of the parameter l/δ, where l/δ is the ratio of the length of the spike to the standoff distance of the bow shock at stagation ponit. It was observed that for $l/\delta \leq 0.7$ the flow detaches from the spike tip and remains steady, for $1.1 \leq l/\delta \leq 2.2$ the flow was attached and steady flow while for all other values of l/δ unsteadiness in flow was observed. It was found that the attached and steady flow can be maintained by increasing the spike length with cone bluntness ratio. The heat transfer investigation revealed that both the non-spiked and spiked models the heat transfer distribution were independent of the Reynolds number. In the case of detached spike flow, the heat flux distributions were fundamentally unchanged from those measured on the non-spiked models whereas for the attached spike flow, the maximum heat flux value were less than the non-spiked stagnation point values and occurred at the reattachment point of the model. It was also found that the total heat transfer rates to the model increased with the spike length for the steady spike flows, with values in the range of 1.1 to 1.3 times the non-spiked values.

Carlos Zorea and Josef Rom in 1970 [26] did experimental investigation at aerodynamic laboratory of Israel Institute of Technology, Haifa, Israel to study the aerodynamic characteristics of a supersonic vehicle using aerospikes for a freestream Mach number 1.5 and 2.25. The lengths of the spike were varied between 0, 0.5, 1.0, 1.5 and 2.0. They found that at a certain critical spike length, a maximum reduction in drag was observed beyond which the effectiveness of the spike is greatly reduced. Also an increase in angle of attack yields to a reduction in drag. The effect of drag reduction vanishes for $\alpha \geq 15°$.

Guenther R A and Reding J P [27] in 1977 investigated the fluctuating pressure on a drag reduction spike. The models investigated were blunt ogive cylindrical model fitted with a telescopic aerospike with a blunt aerodisk the tip. The regimes considered for flow simulations were transonic and supersonic flows. For an angle of attack greater than zero degree, large fluctuating pressures were observed on the sides of the spike base at transonic speeds, which are associated with non-axisymmetric flows. For angle of attack greater than 7 degrees at supersonic speed, high pressure fluctuations were observed on the windward side of the nose cap which is the result of intermittent shock-shock interaction. It was found that the drag can be reduced further by combining the two dead air zones i.e. merging of dead air zones ahead of the main body and with the dead air zone in wake generated behind the blunt aerodisk tip.

Khlebnikov VS [28] in 1986 did a focused study on the heat transfer measurement of a spherical model with an aerospike for a freestream Mach number 3 and Reynolds number of 1.4 x 10^6. The length of the spike rod was varied from 0.283 to 1.78 of the base geometry diameter. The aerodisks considered for the investigation were pyramidal and conical disk which were mounted at the tip of the spike. He concluded that the maximum value of heat flux varies inversely with its distance from the spike root.

A numerical study was done by **Shoemaker J M** in 1990 [29] by solving 2-D Navier-Stokes equation for gross flowfield and axial forces at zero angle of attack of a blunt cone having an aerospike. He considered a flow at $M_\infty = 2.5$ and validated the results with experimental data found for the blunt bodies. Numerical code was applied to hemispherical cylinder with a series of aerospikes to study the optimal length of the aerospike. The optimum *l/D* ratio was found to be 0.83 at Mach number 2.5 which has highest drag reduction. It was found that the aerospike was very effective in drag reduction for the Mach numbers greater than 1.5.

Yamauchi et.al [30] in 1993 studied numerically the effect of supersonic flow over a spiked blunt body at a freestream Mach numbers of 2.01, 4.15 and 6.8. The diameters of the hemispherical base body were considered to be unity and the spike geometry consisted of conical nose with a cylindrical body. The *l/D* ratios of the aerospike were varied between 0.5 *D*, 1.0 *D* and 2.0 *D*. It was found that the drag mainly depends on the length of the spike and on the pressure at the surface in the separated region. It was also observed that for the longer spikes the area of the separated region is extended, but not much influence by an increase in freestream Mach number. Besides these, the change in in flow patterns were observed for 0° and 10° angles of attack and was found that spiral flow occurs on the blunt body at higher angle of attack. Significant pressure variations were also seen for spiked blunt body when the angle of attack was 10° as compared to when the angle of attack is 0°.

Huebner et.al [31] in 1995 experimentally studied the feasibility of spiked bodies for hypersonic missiles. The wind tunnel tests were conducted at Mach number of 6.0 and freestream Reynolds number of 0.8×10^6/ft to obtain surface pressure and temperature history. These data were used to determine the range that the spike would perform the best in terms of aerodynamic heating and reduction in drag for a wide range of incidence angle. The base model used in the investigation was a hemisphere cylinder and the aerospike used was an aerodisk with a flat faced nose. The spike length to diameter of the body was 3 while the angles of attack were varied from 0° to 40°. They concluded that at low angles of attack, less than 5°, the aerodisks are highly effective in reducing wave drag. The surface pressure and temperature data at Mach number 6.0 and Reynolds number 0.8×10^6/ft through wind tunnel test are generated by authors for exposing the aerodynamic heating and drag reduction incidence angle of a spike. The results obtained indicated that the aerospike is effective for very low angles of attack i.e. less than 5°. For angles of attack more than 5°, the impingement of the aerospike bow shock and the flow separation shock from the recirculation region created by the aerospike causes pressure and temperature rise on the windward side of the dome which exceed the values observed in the same region with the aerospike removed.

Ameer G. Mikhal in 1996 [32] numerically studied steady and unsteady flowfields behaviour for spiked projectile nose with vortex ring. The computations were performed at supersonic freestream Mach number of 1.9, 3.0 and 3.5 with a flow field dominated by vortex. Drag at zero degree angle of attack were computed and found to be in good agreement with the experimental data obtained at same Mach number. It was found that at Mach number 1.9 the flow is oscillatory buzzing.

Yamauchi et.al [33] in 1995 numerically studied the effect of spike length, Mach number and angle of attack on the flowfield around spiked blunt bodies at supersonic speeds. It was found that the flow at zero degree angle of attack is characterized by the presence of conical shock wave, a separated region in front of the body and the resulting reattachment shock wave. It was observed that the drag is greatly influenced by the length of the aerospike, which affects the pressure of the surface in the separated region on the front face of the blunt body. The area of the separated region is extended by the longer spike, but is not influenced by the Mach number. It was found that there is the reduction in the pressure levels in the separated region which causes a reduction in drag. It was also found that at slightly higher angles of attacks the flow becomes spiral and complex but the drag coefficients remain at low values.

Mehta RC and Jayachandran T [34] and **Mehta RC** [35] in 1997 numerically studied the effect of viscous flow around a heat shield of launch vehicle. The studies were performed for both hemisphere-cylinders with and without forward facing spike. Reynolds Averaged Navier-Stokes equation was discretised using cell-centred finite volume and solved with a time marching approach. The freestream Mach number ranged from transonic to supersonic flow i.e. 0.9 to 3.0 and Reynolds number ranged from 33.5×10^6 to 46.75×10^6 per meter. Both experimental and computed results obtained for typical heat shield without forward facing spike showed good agreement with each other. It was observed that for spiked blunt body the flow separation zone depends on the Mach number and an increase in the Mach number results in separation conical angle to become sharper. It was also found that the bow shock angle increase because of the presence of spike and deployment of forward facing spike gives a reduction in drag.

Feszty et al. [36] in 2000 carried out numerical simulation over axisymmetric spiked blunt body in supersonic and hypersonic flow regimes of Mach numbers 2.21 and 6 respectively and at Reynolds number to 0.12×10^6 for supersonic flow and 0.13×10^6 for hypersonic flow, based on the diameter of the blunt body. The diameter of the base body was set as unity while length of the spike was made equal to the diameter of the blunt body with spike diameter is $0.06D$ and cone angle at the tip of the spike of 30°. An implicit upwind algorithm based on Roe's scheme was used in conjunction with time marching procedure to solve the transient, compressible Navier Stokes equations so as to study the nature of pulsating flow over spiked blunt body. It was found that the experimental and computed results were almost identical in terms of predicted time periods, while the computed pressure amplitudes were marginally underestimated in supersonic flow and overestimated in the hypersonic flow. Qualitatively both the computed and experimental data showed that the flow features were in good agreement. It was also confirmed that annular jet is formed at the foreshock-aftershock interaction which inflated the separation region to move extra downstream.

Mehta R C [37, 38] investigated numerically, the effect of pressure oscillations over axisymmetric forward facing spiked blunt body. The time dependent axisymmetric Navier stokes equation were solved using Runge-Kutta time integration for freestream Mach number of 6.8. Conical aerospike with hemispherical nose as a base body were considered with *l/D* ratio varied between 0.5 and 2. A periodic pressure variation was observed on both spike and on hemisphere cylindrical body surface.

Another numerical study related to heat transfer over a spiked blunt body was done by **Mehta R C** [39] [40] in 2000 for a freestream Mach number of 6.8. The geometry studied was a hemispherical cone with a pointed aerospike ahead of it and the flow was assumed to be laminar. The studies were conducted on conical aerospike and hemispherical aerospike of various *l/D* ratios of 0.5, 1.0 and 2.0 suggests that a conical shock wave generated at the tip of the spike in a separated region ahead of the main body and extend up to the reattachment point. The peak heating and local maximum pressure was found to be at the reattachment point because of the shear layer created by the spike, which passes through the reattachment shock wave. It was also observed that as compared to an aerospike the aerodisk performed well in terms of drag reduction and aerodynamic heating reduction.

Noboru Motoyama et al. in 2001 [41] did an experimental investigation for drag reduction and thermal protection by using an aerospike for a freestream Mach number 7 and Reynolds number 4×10^5 over a hemispherical body. The effects of aerospike and aerodisk on hemispherical ceramic body were investigated with two different *l/D* ratios of 0.5 and 1.0. The aerospike tested were hemispherical, flat faced and conical in shape and had diameters of either 10 *mm* or 20 *mm* while the diameter of base hemispherical body was 40*mm*. It was found that the hemispherical aerodisk of *l/D* =1.0 with 10 *mm* diameter gives less reduction in drag and heating in comparison to *l/D* =0.5. It was also concluded that the aerodisks give more drag reduction than the aerospikes.

Milicev et al. [42] [43] experimentally studied the effect of aerospike on flow past a blunt body at supersonic Mach number of 1.89 and Reynolds number of 3.8 x 10^5. The model was equipped with four aerospikes of *l/D* = 1, and different shapes viz. conical, cylindrical, pointed cylindrical and rounded and the angle of attack was varied from -4° to10°. It was found that the aerospike shape influences the aerodynamic characteristics of the model but the effect reduces with increase in the angle of attack. The spike with rounded tip and cylindrical body had the best aerodynamic characteristics while the aerospike with rounded tip has the maximum reduction in drag along with a favorable increment in lift.

Feszty et al. [44] in 2002 used computational fluid dynamics techniques to investigate unsteady flow over a spiked body for a freestream Mach number of 2.21 and 6.0, and Reynolds number of 0.12 x 10^6 and 0.13 x 10^6 respectively based on diameter of the blunt body. The aerospike *l/D* ratios used in the investigation were 1 and 2. It was observed that a pulsation in flow is mainly driven by inviscid phenomena. An axisymmetric laminar flow simulation was done to examine the individual flow modes of pulsation and oscillation and was observed that the pulsation flow mode is mainly driven by inviscid mechanism while oscillation flow mode was driven by viscous mechanism.

Studies for hypersonic flow over highly blunt cones with forward facing spike were also conducted by **Viren Menezes et al.** in 2002 [45] and 2003 [46]. Four different spiked configurations with hemispherical, flat faced, flat face aerospike and conical aerospikes were investigated while the *l/D* ratio for all the spikes was kept to be 1. It was concluded that due to a strong shock generated ahead of the blunt body in the high speed regime, an elevation in pressure and aerodynamic heating levels were attained by the downstream flow. The drag reduction obtained was 40 to 50% for a freestream Mach number of 5.75 for a 120 degree apex angle blunt cone with forward facing aerospike having flat aerodisk at small angles of attack. Aerospikes without aerodisk did not result in substantial reduction in drag and an increase in the drag was observed at higher angle of attack due to impingement of the flow separation shock on the windward side of the cone. That means, by altering the flow pattern ahead of the blunt nose of the vehicle the excessive drag and heating loads can be reduced. They also suggested that the aerodisks are more efficient as compared to aerospikes in reducing the aerodynamic thermal loads and drag.

P. Gnemmi et al. [47] in 2003 did both experimental and numerical study of the flowfield around a hemispherical body fitted with a forward facing spike for large range of angles of attacks between 0° and 24° at a freestream Mach number of 4.5. The geometries studied were a hemispherical blunt body, a conical tipped spike, a disk tipped aerospike and a sphere tipped aerospike. The experiments were carried out at a high pressure shock tunnel using a shock tube facility at the French-German Research Institute - Saint-Louis (ISL) while the numerical study was carried out using a Navier Stokes solver in order to calculate lift, drag and pitching moments. Both computational and experimental data were in good agreement with each other especially at high angles of attack. Higher drag reductions were observed from 0° up to 21° for the spherical aerospike as compared to the disk spike and biconical aerospike. However an increase in lift to drag ratio was observed for 21, 26 and 28 degrees while an increase in pitching moment was observed for all spikes and for all angles of attack.

Hirotoshi Kubota in 2004 [48] did a detailed study of the aerothermodynamics and aerodynamics characteristics of reusable launch vehicles. He found that using forward facing aerospike in launch vehicles is useful for reduction both aerodynamic drag and aerodynamic heating.

Srinivasan and Chamberlain in 2004 [49] studied the drag reduction by means of heat addition to the separated region of turbulent boundary layer by combustion of hydrogen gas. Two geometries were considered viz. a hemispherical nosed body with an spike and an ogive nosed body with an aerospike at a Mach number of 2.2. It was found that spiked ogive nose cylinder and hemispherical nose cylinder had shown 35%-40% reduction in drag, beyond that produced by conventional aerospike, because of hydrogen combustion. Numerical simulations were also carried out for hydrogen injection without combustion and it was found that reattachment shock was not eliminated. The additional drag reduction was found to be a result of the main shock wave getting diffused and also the elimination of shear layer reattachment shockwave on the blunt body.

Muhammad Asif et al. [50] in 2004 did numerical simulations on supersonic and hypersonic flow around forward facing aerospikes attached to a blunt body. Aerospike of different geometries and *l/D* ratios were investigated to study the flow around the forebody and its influence on static aerodynamic coefficients. The influence of the aerospike shapes on the aerodynamic coefficients was investigated at Mach number 1.89 and Reynolds number of 0.38×10^6 per meter and angle of attack between 0° to 10°. The second set of investigation were made to study the effect of *l/D* ratio on the aerodynamic coefficient at Mach numbers of 5, 6.8 and 8, and a Reynolds number of 1×10^6 per meter and angles of attack 0, 2 and 6 degrees. It was found that the shapes of the aerospike influence the aerodynamic parameter but the effect reduces with increase in the angle of attack. Aerospike with hemispherical nose and cylindrical body showed the minimum drag coefficient and maximum lift coefficient in the supersonic flow regime. In the case of hypersonic flows, an increase in *l/D* ratio results in reduction in drag but with a substantial loss of static stability. In both the cases the flow around the aerospike is featured by a conical shock emanating from the tip with a separated region in front of the forebody resulting in reattachment shockwave.

Jagadeesh Gopalan et al. in 2005 [51] studied the flowfield around a blunt cone with120 degree apex angle fitted with a forward facing aerospike. The geometries of the aerospikes considered in the study were a conical tipped aerospike and disc tipped aerospike. The ratio of length to base diameter (*l/D*) for all aerospikes was taken as 1 and all the experiments and numerical simulations were conducted at freestream Mach number 6.99 and Reynolds number 2.46 x 10^6 per unit length. The results obtained indicates that only slight oscillations appears near the edge of the cone when fitted with a disc nosed aerospike and when the model is fitted with a conical aerospike the shock oscillations seems to be more noticeable and clear. However, in the experimental results no pulsation flow mode was observed.

Hiroaki Kobayashi et al. in 2007 [52] did experimental investigation to study multidisk telescopic aerospike using stabilizer disk. It was found that changing length of the telescopic aerospike causes a buzzing phenomenon which contributes to spurious pressure oscillations on the surface. The telescopic aerospike using stabilizer disk was studied for a freestream Mach number ranges from 1.1 to 5.1, Reynolds number 0.845 x 10^7 to 2.31 x 10^7 per meter. It was found that a stabilizer disk on the surface of the aerospike yields a stable recirculating region which divides the single separated flow over the surface into a number of conical cavity flows irrespective of any change in length. A decrease in the induced drag and zero lift drag was observed for aerospikes with multiple disks. The aerodynamic stability effectively improves by providing cavities on the conical surface.

Kalimuthu et al. in 2008 [53], 2010 [54] and 2013 [55] studied the aerodynamic characteristics of a hemispherical body using forward facing aerospike and aerodisks. The research was aimed at measuring pressure and force on blunt body with flat faced aerospike, hemispherical aerospike, hemispherical aerodisk and flat face aerodisk for a freestream Mach number 6.0. The *l/D* ratio was varied between 0.5, 1.0, 1.5 and 2.0 while the angle of attack was varied from 0 to 8 degrees. They observed that forward facing aerospike attached to the blunt hemispherical body changes the flowfield and reduce the drag coefficient by creating recirculating region across the stagnation point of the blunt body. They also observed that for more efficient drag reduction, the reattachment point of shear layer ought to be moved more backward by considering optimal aerospike length. It was concluded that aerodisk with *l/D* =2.0 is most effective among the models investigated and also that aerodisks are superior to the aerospikes for reduction in drag.

Gauer M and Paull A in 2008 [56] did numerical investigation for heat transfer and drag reduction of a nose cone with forward facing aerospike of varying length. The freestream Mach number considered were 5.0, 7.0 and 10.0 while the *l/D* ratios of aerospikes were varied between 1 and 4. The tip of the aerospike was modified so as to have different bow shock shapes. The tip geometry included a dome shape, a sharp front and a blunt aerospike. It was observed that the reduction in drag was 2% for bodies with shorter blunt aerospike and 53% for the ones with longer blunt aerospike. Though the sharp aerospike yields 35% reduction in drag but it results in an increase in the heat flux because of smaller shock angle compared with the blunt aerospike. It was observed that use of aerodome i.e. dome shaped aerodisk results in no shock impingement and reduces a drag up to 62%, and heat flux up to 85%.

Mehta RC in 2010 [57] conducted numerical studies on a hemispherical cone with flat aerodisk, conical aerodisk and hemispherical aerodisk aerospikes protruding ahead of the hemispherical dome at a freestream Mach number 6.0. The *l/D* ratio was varied from 0.5*D* to 2*D* while all the numerical simulations were performed at zero degree angle of attack. All the computed data were found to be in good agreement with the experimental data. It has suggested that the bow shocks wave over the flat disk and spherical disk aerospike provides different separation zone in the neighbourhood of the spiked blunt body. Thus the flowfield behind the aerodisk was found to be more complex when compared to the one for body with conical aerospike. It was found that choosing the optimal aerospike length shifts the shear layer reattachment point on the hemispherical body with suitable consideration of the aerospike nose geometry. The flow was assumed to be laminar and followed an axisymmetric domain for computation. The drag on the hemispherical body was greatly influenced by the aerospike geometry and aerospike length.

Gerdroodbary and Hosseinalipour in 2010 [58] did numerical simulations were performed to study the drag and heat transfer over a highly blunted cone with forward facing aerospikes for a freestream Mach number of 5.75 and Reynolds number of 1.5×10^6. The geometry of the aerospike studied were cut aerospike, sharp aerospike, flat aerodisk aerospike and hemispherical disk aerospike and the *l/D* ratio varied from 0.3 to 1.5. It was found that an increase in *l/D* ratio results in sharp reduction in drag. The hemispherical aerodisk aerospike results in maximum reduction in drag of up to 70% as compared to cut aerospike which showed a reduction in drag of 60%. Also an increase in the angle of attack results in the decrease in the drag reduction because of non-shifting of separation point further away from the nose cone.

In the same year **Humieres and Stollery** [59] did experimental investigation on the 1:100 scaled down model of Apollo re-entry vehicle. The diameter of the projected body was kept to be 39 *mm* and the spherical cap radius was equal to 36 *mm* while the diameter of the cylindrical aerospike was 2 *mm* which was fitted with a conical tip. The *l/D* ratio of aerospikes investigated were 0, 0.125, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2.125 for a freestream Mach number of 8.2 and a Reynolds number of 9.01×10^6. The experimental study revealed that no unsteadiness in the flow was detected for all the aerospike lengths investigated and a reduction in drag was observed for the shorter aerospikes. It was further suggested that drag produced by the spiked body can be approximated by the pressure drag generated by a solid cone, with some correction.

Ahmed and Qin in 2010 [60] did an extensive research in the area of drag reduction mechanism for hemispherical body flying at hypersonic speed. He found that a blunt body, when flying at hypersonic speed experiences excessive aerodynamic heating and large increase in pressure drag which could possibly be reduced by deploying an aerodisks at the stagnation point of the main body. The *l/D* ratios of the aerospikes investigated were varied up to 2.5 and the diameter of the aerodisk selected was 0.4 times the body diameter. Based on the numerical investigation, they explained that the dividing streamline of the shear layer was assumed to be the outline of the effective body which replaces the original spiked hemispherical body that effective body shape and the flow stability depends on the energy level of the dividing stream. They concluded that the aerodisks is more effective in reducing aerodynamic drag than aerospikes when the separation point is shifted on the aerospike axis, reducing the downstream pressure by the formation of expansion fans at the shoulder of the aerodisk. It was also observed that the drag reduction mainly depends upon the size of the aerodisk and the length of the aerospike. An optimum aerodisk size for a specific aerospike length produced minimum drag which was found to be inversely proportional to the aerospike length.

D. Sahoo et al. in 2013 [61] did experimental investigation to study the steady state and unsteady flow features over a spiked blunt body at supersonic freestream Mach number of 2.0. The geometries of the aerospikes studied were spherical blunt tip, sharp tip and aerodisk at zero degree angle of attack. It was found that an aerodisk results 46% in drag reduction while a sharp tip results 31% reduction in drag. The increase in unsteadiness was observed with the adoption of the aerospike. Experiment and computational results showed that the spectrums of flow oscillations were of similar trends but the magnitude were different. The computations for steady flow results showed good agreement with experimental data. However for unsteady flowfield, the computation was initially made for laminar and after obtaining steady state solution, transient computations were made with very small time steps to capture the unsteadiness of flow. It was found that experiment and computational data for the unsteady flow does not show results in good agreement.

Mansour and Khorsandi in 2014[62] did numerical simulations to study the effect of aerospikes on a blunt body when flying at hypersonic Mach number of 6. It was observed that the flow past an aerospike form a conical shock wave which remains away from the blunt body. This shockwave detaches from the aerospike and forms a conical recirculating zone in the area surrounding the stagnation region. Due to this the reduction in dynamic pressure is observed which reduces the pressure drag and wall heat fluxes on the forward facing region of the hemispherical base body. It was also observed that the shear layer reattaches at the shoulder of the hemispherical body thereby increasing the pressure and local heat flux. It was found that the drag coefficient of the spiked body is reduced by almost 40% with respect to base body.

Gerdroodbary et al. in 2014 [63] studied numerically the effectiveness of the coolant film by injecting various counter flowing jets from the tip of the nose with aerodisk aerospike. The various features of the counter flowing jets on the hemispherical cone surface were numerically simulated to study the performance of jet on heat reduction at the surface of the nose cone. The unsteady axisymmetric compressible Navier-Stokes equations with and without gas injection are solved for a freestream Mach number 5.75 at zero degree angle of attack. Reductions in heat fluxes were observed for various conditions of jet. For a low pressure ratio even a negative heat flux was observed which indicates that the flow is wetting the model and results in cooling effect which significantly affects the thermal protection system. Also it was observed that the aerospike length influences the cooling performance and changes the flow structure of the recirculating region. The increase in the aerospike length yields reduction in the heat fluxes whereas for a shorter aerospike a strong bow shock is observed which increases the heat flux at the nose cone. Thus it has been concluded that the counter flow jet is highly effective for drag and heat reduction in combination with aerospike.

Yadav R and Guven U in 2014 [64] did numerical simulation of a hemispherical body fitted with two axisymmetric aerodisks in series at the stagnation point of the base body for a freestream Mach number of 10.1 and Reynolds number 4.3 x 10^7 per meter. The studies were meant to analyse the heat transfer rates and aerodynamic drag on a hemispherical cylinder using double disk aerospike for different *l/D* ratios of 1, 1.25 and 1.5. A slight reduction in aerodynamic drag with no reduction in aerodynamic heating was observed for shorter aerospike. The aerospike with *l/D*=1.5 yielded maximum drag reduction of 44% along with 9% reduction in reattachment heat flux. It was also observed that in comparison to single aerospike, double disk aerospikes are more advantageous in reducing aerodynamic heating and drag of the main body. It was concluded that "if aerospikes are to be used for hypersonic vehicles, it has to be multidisk aerospikes in series".

D. Sahoo et al. in 2016 [65] studied the flowfield characteristics of various aerospike with different shapes and length experimentally and computationally, at Mach number of 2.0 and at zero angle of attack. The different geometric shape of the aerospike investigated were sharp tip aerospike, flat tip aerospike and spherically blunted tip aerospike. It was found that the changes in the spike length and shape result in considerable change in the drag. The maximum drag reduction observed was 46.80% .For an *l/D* =1.5, a drag reduction of 45.40% is observed for sharp aerospike. They also observed unsteadiness in the flow, and found that change in the aerospike shape from sharp aerospike to blunt aerospike for a particular length of the aerospike reduces unsteadiness in the flowfield.

Based on an exclusive literature survey on aerodynamics and aerothermodynamics of blunt bodies for heat and drag reduction using aerospike and aerodisk the following conclusion can be drawn:

a. The reduction of drag by plain and aerodisk aerospike is well established with the aerodisk being superior to pointed aerospikes.

b. Most research focuses on the effect of *l/D* ratio of the aerospikes and only few papers reports the effect of aerodisk shape and size on the aerodynamic drag and aerodynamic heating of a blunt body.

c. Investigations have shown that certain length and tip design the aerospike can reduce aerodynamic heating to some extent. However most researches are done with laminar assumptions or tested under laminar conditions. Some researches with turbulence considerations have reported detrimental reattachment heat fluxes and increased heat transfer rates to the main body.

d. Aerospikes and aerodisks of certain length make the flow unstable and pulsating which is highly undesirable. The multi row disks or aerospikes with stabilizers or multidisk aerospikes can make the flow stable. However, very less work has been done for 2-disk or multiple disk aerospikes for reduction in drag and aerodynamic heating.

In view of the conclusions made in regard to the study of spiked blunt bodies at hypersonic speeds an exhaustive investigation is warranted. Although the aerospikes reduce drag the associated high heating rates can be reduced by using aerospikes with multiple aerodisks. Multiple aerodisks, besides reducing large reattachment heat fluxes, can also make the flowfield ahead of the blunt body stable which is highly desirable for navigation and structural requirements. In this regard, the aerospikes with two and three disk aerospikes of varying length, sizes, shapes and relative positions on the spike are investigated for their effectiveness in reducing aerodynamic drag, reattachment heat fluxes and the total heat transfer rates to the blunt body at hypersonic speeds.