

Computational Study on Role of Pimples in Ballistic Entry of Space Vehicles

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Abstract: This paper presents the study of hypersonic fluid flow over the blunt nosed body and the effectiveness of pimples in order to alleviate the aerodynamic heating of space vehicle during ballistic entry. Comparative study has been carried on conventional blunt nosed body and pimples blunt nosed body to evaluate the alleviating degree of aerodynamic heating. From the preceding study, it has been observed that the pimples blunt nosed body significantly alleviates the aerodynamic heating, in the sense of reducing the curvature of shock wave. Numerical Simulation using Ansys-Fluent is carried out to evaluate effectiveness of Pimple by varying its geometrical definition, which provides lots of insight of Shockwave and its thermal interaction with the solid body. Structural Analysis is carried out to study the thermal distribution across the solid body and thermal stress concentration due to aerodynamic heating. System Coupling Technique is used to study the interaction of fluid flow over the solid body and thermal behaviour of Solid body simultaneously. Numerically, it has been observed that the Pimples Blunt nosed body plays an extensive role in alleviation of aerodynamic heating relative to its conventional blunt nosed body.

Keywords: Aerodynamic heating, Shockwave, Blunt Nosed Body, Numerical Simulation, System Coupling

I.INTRODUCTION

Hypersonic flight has revolutionized both commercial as well as military activity. The economic implications of affordable high-speed flight become apparent when one recognizes that hypersonic flight is an essential element at some point in the trajectory of all space vehicles during ascent, and, if applicable, descent as well [1]. Future hypersonic vehicles may also facilitate rapid transport between distant points on the earth at a fraction of the time it currently takes [15]. Aerothermodynamics refers to the distribution of pressure, forces, moments, and heating on the vehicle. At high velocities and enthalpies, these are very large, and their minimization requires compromise between conflicting considerations [6]. The nose of the vehicle plays a very important role in the design of hypersonic vehicles. For the blunt body, the shock is curved and stands off (i.e., is detached) from the body – the region between the shock and the surface is termed a shock layer [2]. The shock layer is thus a highly vortical region and is often termed an entropy layer. For the sharp-nosed configuration, the shock is weaker and is attached to the surface at its tip [10]. It should be noted that even for a sharp-nosed body, there is always some bluntness at the leading edge, but the radius of curvature can be very small. For sharp-nosed objects, the angle between the shock and the surface becomes very small at hypersonic speeds. Drag is also an important consideration for vehicle design. Blunt noses, while reducing peak

heating, increase drag on the body [5]. This is fortuitous for vehicles such (as those of below figure 1), which essentially perform braking missions by presenting flat surfaces to the incoming flow [4]. For ballistic trajectories, however, range is an important consideration and drag exerted in the lower atmosphere must be reduced. These vehicles therefore tend to be relatively slender, with slightly blunted noses that experience severe heating but only for short times [7]. For such vehicles, turbulent skin friction can then be a major determinant of drag, and asymmetric laminar-turbulent transition locations can yield unanticipated moments. Finally, advances in hypersonic theory have been constrained by the difficulty in experimentation and simulation, although active research is lifting many of these limitations [9]. Flight tests are expensive and difficult to monitor while ground tests cannot simultaneously match all conditions such as Mach and Reynolds numbers as well as enthalpies for larger vehicles [3]. Nevertheless, Computational Fluid Dynamics (Numerical Simulation) has a provision to simulate the flight test at required boundary conditions [8].

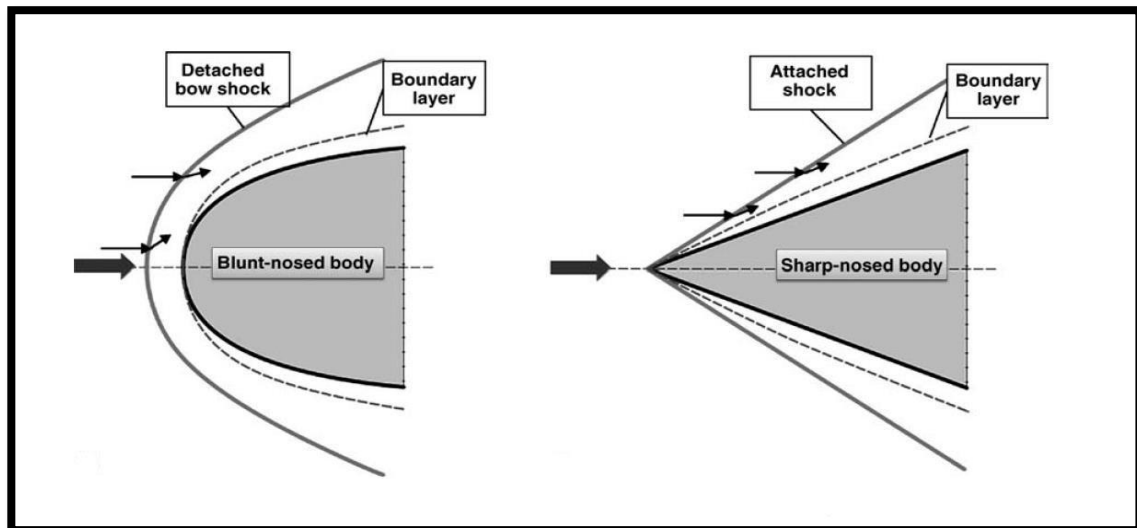


Fig 1: Bow shock wave formation in blunt nose body and sharp nose body at hypersonic condition

Its primary scope is to choose the optimum design of Blunt nosed body, in order to alleviate the aerodynamic heating due to viscous effects, with the aid of pimples. Comparative study has been carried out numerically on conventional Blunt nosed body and Pimpled Blunt nosed Body. And the effectiveness is evaluated against each other by observing the scattering of thermal energy (Temperature) over the surface of Blunt body. If the Pimpled Blunt Nosed body depreciates the scattering of thermal energy, geometrical definition is varied in such a way of increasing its radius.

II. GEOMETRICAL CONFIGURATIONS

The CAD model is developed for both Blunt Nosed Body and Pimpled blunt nosed body in CATIA V5 software (as shown in figure 2&3).

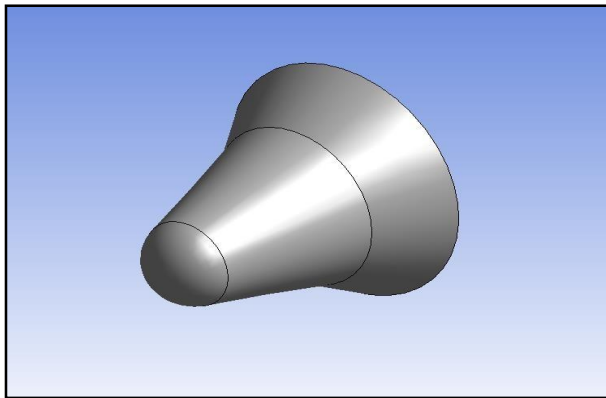


Fig 2: Existing Parabola nose cone model

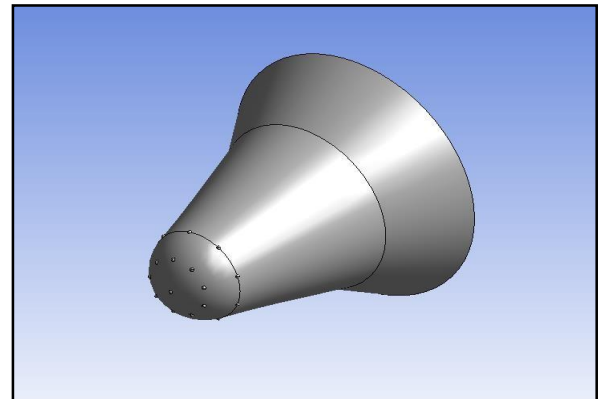


Fig 3: Proposed Pimpled parabola nose cone model

Surface Mesh

Skewness Quality of both cases is chosen to 0.4 and the Mesh count of Conventional & Pimpled Blunt Nosed Body about 81,220 and 92,645 respectively (as shown in figure 4&5).

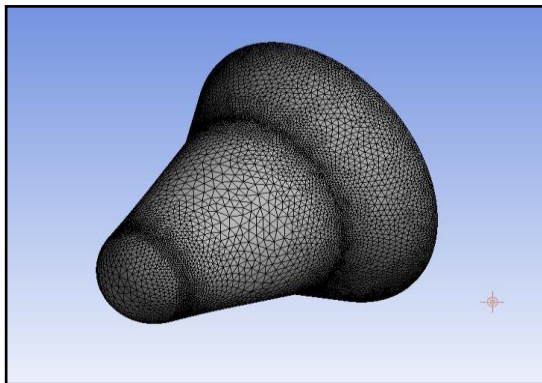


Fig 4: surface mesh on Existing nose cone

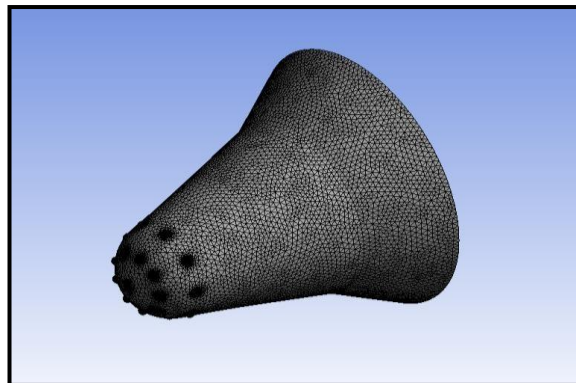


Fig 5: surface mesh on pimpled nose cone

III. DISCUSSION ON EFFECTIVENESS OF PIMPLED & CONVENTIONAL BLUNT BODY

Contour of Mach number:

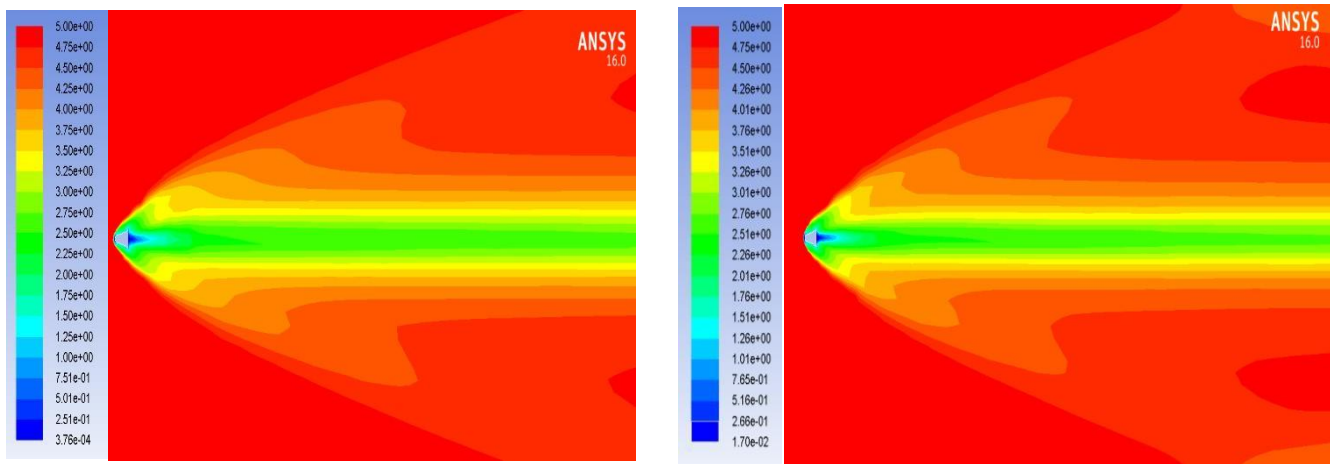


Fig 6: Simulation of the Mach number over the parabolic nose cone without and with pimple surface at Mach no. 5

(From the above figure 6), it is evident that the slope of Bow Shock (Curvature) in Pimpled Blunt nosed Body is significantly greater than the Conventional one due to increase in effective frontal area. Though, the Shockwave can be considered as non-rotating compressor, which transfers the kinetic energy of incoming fluid flow to Internal energy of Fluid by means of increasing the Temperature and Pressure at the downstream of shockwave with significant Pressure Loss and Thermal Dissipation. Those Thermal Dissipation is the only entity, which is triggered by viscous effects to exchange the thermal energy between the fluid and solid surface that are exposed to fluid. Degree of Thermal Dissipation purely depends on the slope of Shockwave, for example, Thermal Dissipation would be greater in Normal Shockwave than in Oblique Shockwave. From the preceding discussions, it is clear that Thermal Dissipation i.e., transfer of thermal energy from the Fluid to Solid surface is greater in Conventional Blunt Body than in Pimpled Blunt Nosed Body.

IV. DISCUSSION ON EFFECTIVENESS OF PIMPLE CONFIGURATION – PIMPLED BLUNT NOSED BODY

From the preceding conclusion, Entropy gradient (region form the Solid Surface to shockwave), where the fluid molecules tends to share their thermal – kinetic energy with the adjacent fluid and solid molecules, Pimples present over the nose of the body retards the exchange of energies with the aid of consecutive infinite number of compression and expansion waves. But, the Pimple geometrical definition (shape) plays a vital role in distracting the vortical structures present within the thin shockwave that results in destructing the geometrical structure of Bow Shockwave. Thus, Numerical Study can be carried out on different pimple geometrical configuration in order to determine the optimum Pimple geometry. Three different radius of Pimple are chosen to study numerically and the radius are 10 mm, 15 mm & 20 mm.

Contour of Mach number:

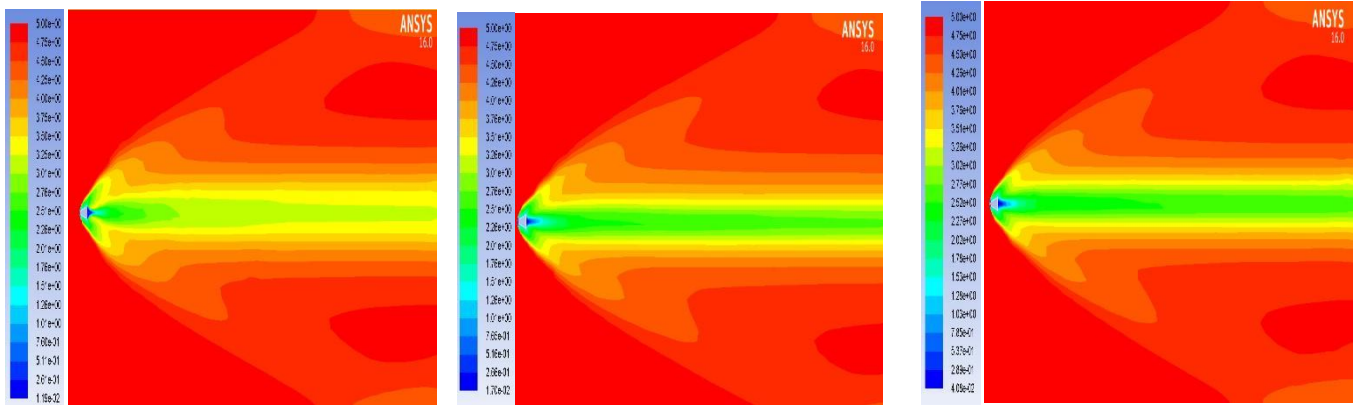


Fig 7: Simulation of the Mach number over the parabolic nose cone without and with pimple (R 10, R15, R20 mm) surface at Mach no. 5

From the above contours of Mach number, it is observed that the Mach number at the nose tip immediate downstream of shockwave goes on decreasing as the radius of pimples increases. Physically, it dictates the fact that radius of Pimples has a profound effect on destructing the geometrical structure of Bow Shockwave in the sense of increasing the slope of shockwave i.e., to reduce the curvature of shockwave at the nose tip by resembling or making the bow shockwave to behave as Normal Shockwave at nose tip. As curvature of bow shockwave decreases, Pressure loss across the shockwave increases at the nose tip, generally thereby reducing the exchange of thermal energy of fluid molecules with the solid surface. Pressure loss across the shockwave increases as the radius increases (as shown in figure 7). Because, the intensity of consecutive generation of infinite number of compression waves (which tries to suppress the energy of fluid) and expansion waves (which tries to recover the energy of fluid) over the pimples increases as the radius increases.

Contour of Pressure:

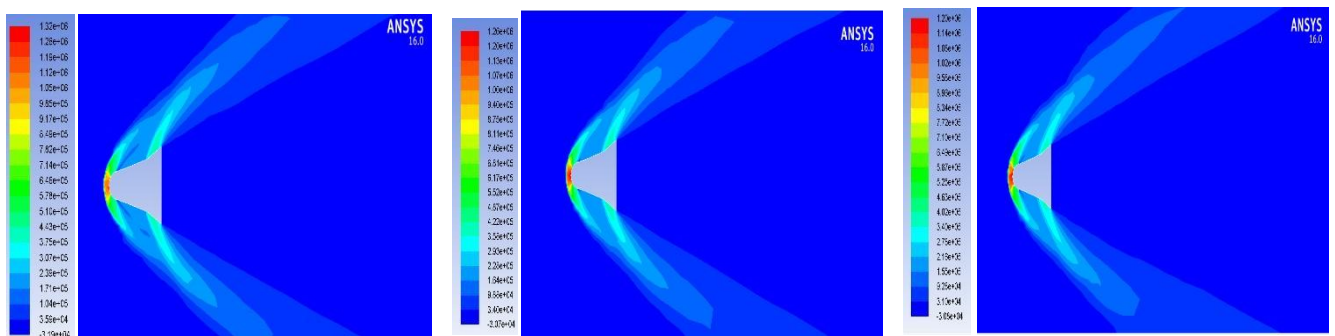


Fig 8: Simulation of the Pressure distribution over the parabolic nose cone without and with pimple (R10, R15, R20 mm) surface at Mach no. 5

Table 1: Simulation analysis pressure distribution results of pimped nose cone (R10, R15, R20 mm) at Mach no 5

Nose Cone Pimple Radius	Pressure Distribution	
	Nose Cone Tip	Another Places
R10 mm	1.13x10 ⁶ Pa	3.75x10 ⁵ Pa
R15 mm	1.19x10 ⁶ Pa	4.22x10 ⁵ Pa
R20 mm	1.20x10 ⁶ Pa	4.87x10 ⁵ Pa

Pressure Contour in Hypersonic Flow is used to visualize the location of both Compression and Expansion Shockwaves and its Geometrical Orientation (as shown in figure 8). From the above Contours, it could be concluded that the intensity of Consecutive generation of both Compression and Expansion wave's increases as the radius of pimple increases, which favors us in the sense of reducing the fluid temperature at the proximity of wall, but it tends to increase the nose temperature.

From the Prefect gas law, Pressure is directly proportional to Temperature. Infinite number of Expansion Waves present around the annulus of Pimped Blunt Nosed Body depreciates the exchange of thermal energy from the fluid molecules to solid molecules. But, Temperature at the nose tip, immediate downstream of Shockwave increase at the rate of effective radius of Solid body, which appreciates the sharing of thermal energy of fluid to solid surface (as shown in Table 1).

Contour of Temperature:

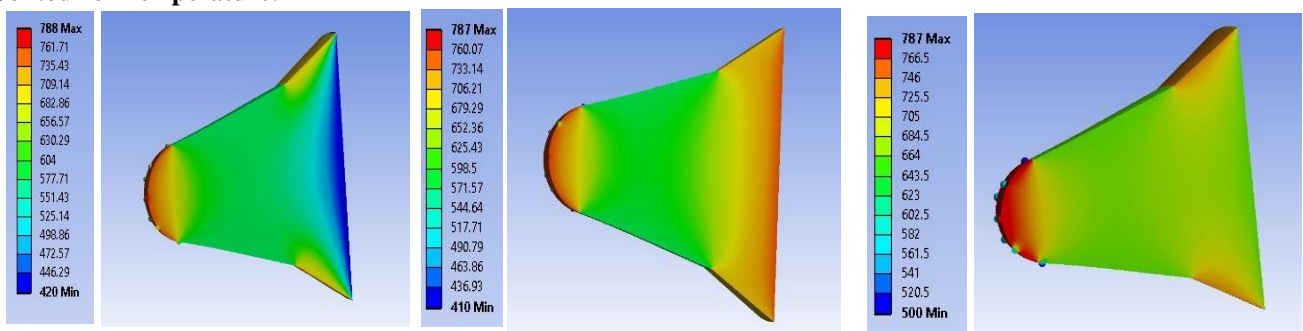


Fig 9: Simulation of the temperature distribution over the parabolic nose cone without and with pimple (R10, R15, R20 mm) surface at Mach no. 5

Table 2: Simulation analysis Temperature distribution results of pimples nose cone (R10, R15, R20 mm) at Mach no 5

Nose Cone Pimple Radius	Temperature Distribution	
	Nose Cone Tip	Another Places
R10 mm	765.57 K	690.25 K
R15 mm	770.65 K	733.14 K
R20 mm	787.60 K	766.50 K

The above Contours of Temperature of three different radius of Pimples dictates the fact that, despite the Pimples has the tendency to reduce the aerodynamics heating of Ballistic Entry vehicles by diffusing the shockwaves. (as shown in figure 9) i.e., in aerodynamic point of view, but Pimples present over the nose of Space body would be subjected to severe tortuous impact of hypersonic fluid flow, thermodynamically it fails to dissociate the heat energy at the nose tip. Another noteworthy fact is that, Coefficient of drag increases as the radius of pimple increases, indeed, the Pimpled Blunt Nosed body tends to behave or resemble like Blunt body with large frontal area, as the radius of pimple increases (as shown in Table 2).

Shear Stress Distribution:

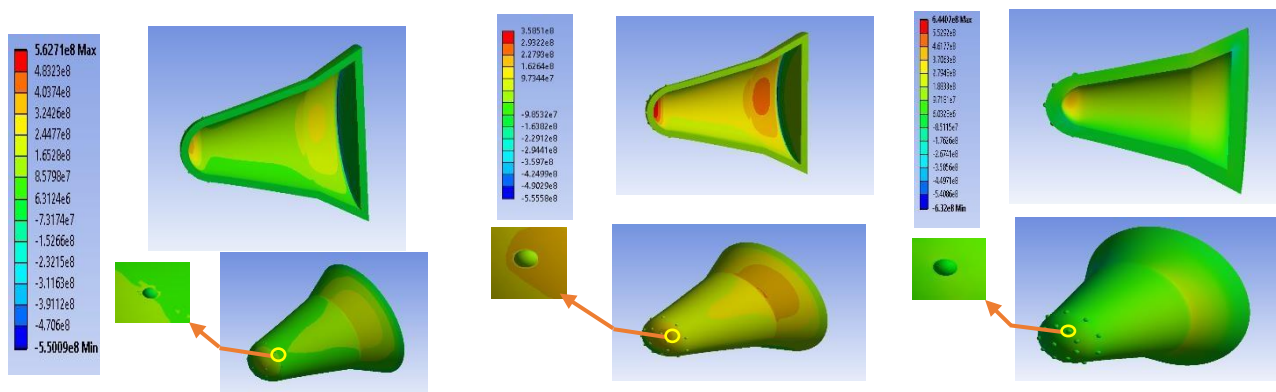


Fig 10: Simulation of the Shear Stress distribution over the parabolic nose cone without and with pimple (R10, R15, R20 mm) surface at Mach no. 5

Table 3: Simulation analysis shear stress distribution results of pimped nose cone (R10, R15, R20 mm) at Mach no 5

Nose Cone Pimple Radius	Shear Stress Distribution	
	Nose Cone Tip	Another Places
R10 mm	3.2426×10^8 Pa	1.6798×10^8 Pa
R15 mm	3.5051×10^8 Pa	8.6793×10^7 Pa
R20 mm	3.7063×10^8 Pa	8.8681×10^7 Pa

Shear Stress distribution dictates the region which is vulnerable to aerodynamic heating. It has been observed that the Shear Stress in Pimple of Pimped R10 Blunt Body (3.2×10^8 Pa) is lesser than in Pimped R15 Blunt Body (9.8×10^7 Pa) (as shown in Table 3). so, it could be concluded that, as the radius of Pimple increases, pimples tends to develop uniform internal reactive stress, which results in less discontinuous variation of thermal shear stress across the pimple. Hence, as the radius increases, Pimples become less vulnerable to aerodynamic heating, despite having very high temperature at the nose tip.

All the above contour of Shear Stress Distribution is just to illustrate the effectiveness of Pimped Blunt Nosed Body over the Conventional Blunt Body, with the assumption, that the inner skin of Space vehicle is free from shear due to aerodynamic heating (as shown in figure 10).

V. CONCLUSION

Numerical Approach is used to appraise the performance of both Conventional Blunt Nosed Body and Pimped Blunt Nosed Body. Conversion of Kinetic Energy of Fluid to Thermal Energy is found to be greater in Conventional Blunt nosed Body than the Pimped Blunt Nosed Body. Thus, the Pimples has the ability to delay or to alleviate the thermal interaction between the solid and fluid molecules, by stretching the shockwave in normal direction, rather than sharing the energy of fluid to other molecules relative to its Conventional Blunt Nosed Body. Though the Pimples reduces the aerodynamic heating of Space body during Ballistic during, it is more vulnerable to thermal shear stress than the conventional one.

As the radius of Pimples increases intensity of Consecutive generation of both Compression and Expansion wave's increases, which favors us in the sense of reducing the fluid temperature at the proximity of wall, but it tends to increase the temperature of nose tip. Conversion of Kinetic Energy of Fluid to Thermal Energy at nose tip is found to be greater as the radius of pimples increases, hence, thermodynamically , larger pimple radii fails to dissociate the heat energy at the nose . Hence, possible smaller radius of pimple has to be chosen to alleviate the temperature of nose tip.

As the radius of Pimple increases, pimples tends to develop uniform internal reactive stress, which results in less discontinuous variation of thermal shear stress across the pimple. Hence, as the radius increases, Pimples become less vulnerable to aerodynamic heating, despite having very high temperature at the nose tip.

Smaller pimple radius has to be chosen to alleviate the temperature at nose tip, whereas larger pimple radius has to be chosen to make the pimple less vulnerable to thermal shear stress. So, the designer has to trade-off between these two conflicting criteria.

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