Survey of Aerospike and Aerodisk Technologies for Drag Reduction at Hypersonic Speeds

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Flight at hypersonic speeds has been a topic of interest in the aerospace field. Sustained flight at such high Mach numbers is complex because of intense aerodynamic heating and drag effects due to shock waves. Heating effects have been mitigated by the ideal blunt body shape of vehicles at this speed, but this configuration increases drag. To attain both thermal protection and drag reduction, technologies such as the aerospike and aerodisk have been investigated to alter the geometry of the body and, thus, of the flow field. Size parameters such as the length of the spike and diameter of the disk have been investigated, with increases in spike length up to the diameter of the blunt body and increases in aerodisk diameter up to 30 mm being shown as optimal. Further, design parameters such as presence or absence of a disk, number of disks, presence of a channel in the spike, and presence of jets have been observed, with varying results. Size parameters and combinations available from previous experiments are compared to determine which would result in greatest drag reduction.

I. Introduction

Hypersonic technology involves flight at speeds higher than Mach 5, and it has long been of great interest within the aerospace field. Notably implemented in the descent of the NASA Mercury, Gemini, and Apollo spacecraft [1] as well as in military transport, hypersonic vehicles would provide key advantages in military flight and atmospheric re-entry as well as advanced future applications of commercial transport. However, development of such systems has been limited due to aerodynamic challenges at such high speeds.

When a body moves at hypersonic speeds, pressure waves are created that pile up in front of its leading edge, creating an area of great pressure and temperature difference between the high-speed air moving around the body and the air in front of the body which has received no warning of the body's presence. Because of this great difference between flow conditions, bodies flying at hypersonic speeds face increased drag due to pressure and greater aerodynamic heating due to a greater flight Mach number [2], which can pose great practical difficulties for sustained flight.

The main configuration tested at these speeds has been the blunt body; though its shape allows for decreased heat load, the blunt nose experiences greater drag from bow shock waves [3, 4, 5, 6], which can make up two-thirds of the total drag [4]. The key to eliminate this drag is to remove the high-pressure region behind the wave [7]. However, it has been difficult to attain this goal while maintaining the heat protection offered by the blunt body. Thus, to retain the thermal benefits of the blunt nose but improve its performance while experiencing high degrees of shock waves, researchers have explored technologies that could be added to the nose to slightly modify its geometry at the leading edge. They aim to alter the flow field around the body by converting a strong bow shock wave into an oblique shock wave, thereby reducing the drag experienced by the body [4].

A simple way to implement this principle is to take advantage of geometric properties of different configurations. For instance, the aerospike—a thin rod attached to the nose of the aircraft [2]—creates an area of separated flow in front of the body that protects it from the high-pressure flow in front of it [8]. In effect, it pushes the shock wave away from the blunt body and thus reduces the drag the body experiences [6]. For further optimization of the flow field, the aerodisk—a thin disk attached to the end of the spike—has been proposed as an alternative to the point of the spike

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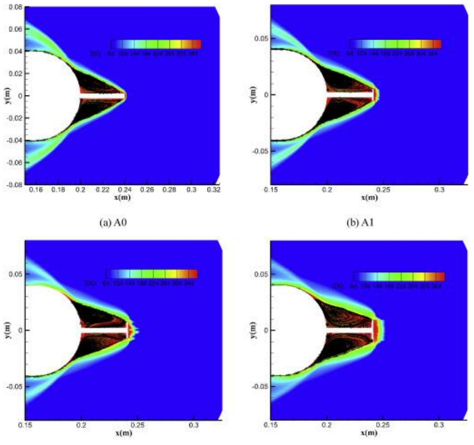
[3] and has been the subject of further research. It is in great interest to know which combination of spike length, number of aerodisks, aerodisk parameters, and alterations to the two technologies presented would provide the most effective drag reduction at hypersonic speeds. The aim of this paper is to survey spike and aerodisk technology and systems created with them to determine which would be the most effective tools to decrease drag.

II. Aerodisk Parameters

The aerodisk's presence on the blunt body allows for an alteration of the flow field at the tip of the blunt body by creating low-pressure flow regions that minimize the sudden change in conditions that a shock wave causes; depending on the length (the distance between the disk and the nose of the blunt body), the number of aerodisks, and the diameter of the disks, different effects in drag reduction can be attained.

A. Diameter

The presence of an aerodisk protects the body from the incoming changes in flow parameters. To maximize these effects, it has been shown that a disk of greater diameter has a greater effect than a disk of smaller diameter in shielding the body from the reattachment shock wave, allowing this somewhat smaller shock wave to attach to the body in a less critical point on the body [6]. The resulting recirculation flow allows for drag resistance and thermal protection in hypersonic flows [9, 10]. Because a decrease in drag varies directly with the size of the recirculating flow, the goal of the hypersonic-aircraft-designer is to maximize the area of recirculating flow in front of the body, as the dynamic pressure in this flow section is much less than that in the other areas of the flow field [8]. Since drag is a function of dynamic pressure, a lower dynamic pressure will create a lower drag force on the body. Also, with an increase in the aerodisk's diameter, the shock wave produced by flight at hypersonic speeds is pushed away from the disk [3].



(a) A0 (b) A1

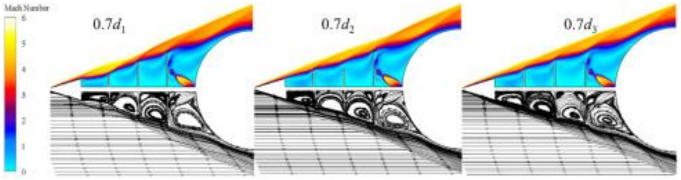
(c) A2 (d) A3

Fig. 1 Recirculation region (in black) for constant spike length and differing aerodisk diameters [8]

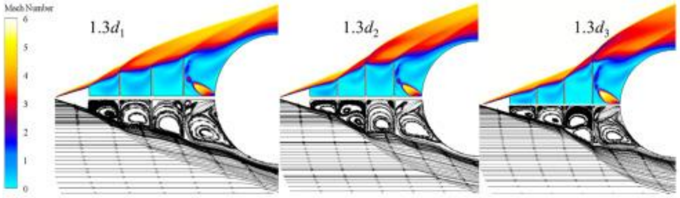
As demonstrated by the figure, configurations with the same spike length experience a greater region of recirculating flow as the diameter of the aerodisk attached to the spike increases. The maximum drag reduction of 54.92% in this experiment occurred with the largest spike (80 mm) and the largest aerodisk (18 mm) [8].

In an experiment in which the spike length was kept constant and the diameter of the aerodisk was changed from 18 mm to 42 mm each time, it was found that the maximum drag reduction occurred at a diameter of 30 mm for the aerodisk [3]. With each increase in diameter until the critical point of minimum drag, the maximum pressure point moved further away from the tip of the blunt body. Because an increase in the aerodisk's diameter leads to a greater region of recirculating separated flow, which protects the body from the incoming high-speed flow, a larger diameter until a certain critical point (in this case, a diameter corresponding to 30 mm) results in lower drag.

Further, in an experiment by Zhang, Xu, et al., a baseline configuration of a conical aerodisk followed by three flat aerodisks in a Mach-6 flow field was simulated [6]. The first flat disk was of a diameter of 30.82 mm, the second flat disk was of a diameter of 45.64 mm, and the third flat disk was of a diameter of 60.48 mm. The increase of the diameter of the first and second aerodisk by 30% provided no significant effect, indicating that the first two aerodisks provide significant drag reduction at 30.82 mm and 45.64 mm, respectively. For the flat aerodisk, 30 mm again appears as an optimal number. By contrast, the increase in the diameter of the third aerodisk significantly impacted the flow field [6]. When its value of 60.48 mm was increased by 30%, the drag experienced by the body increased by 51.34%, the opposite effect than the one desired [6]. The reason could be that the diameter of the third aerodisk is already almost double the optimal diameter found by Zhong, Yan, et al. [3]. Further, the fact that this experiment involved three aerodisks could affect the reaction of the flow field to an increase in diameter of the final disk.



(a) Diameter reduction



(b) Diameter enlargement

Fig. 2 Effect of aerodisk diameter on the flowfield [6]

B. Length

The length of the aerodisk refers to its distance away from the tip of the blunt body; this parameter is most often attained through the use of an aerospike, a thin rod that attaches to the tip of the body and on which the aerodisk is placed. Since the key to reducing drag lies in increasing the recirculation region in front of the body’s nose [8], an aerodisk farther from the body should provide greater shielding from the flow. In multiple studies, it has been found that increasing the length of the aerospike decreases the drag experienced, but there is an optimal point in which drag is minimized, and, past this length, the drag reduction effects are slightly lessened.

Zhao, Shao, and Liu explored five lengths (2, 4, 6, 8, and 12 mm) in their experiments and determined that the strength of the reattachment shock wave decreased as the aerospike length increased from 2 to 6 mm but increased from 6 to 12 mm [5]. Huang, Li, et al. also found that increasing the length of the spike decreases the drag experienced by the body, with the aim to maximize the recirculation region [8].

In a similar study, Zhong, Yan, et al. discovered that, when the diameter of the aerodisk is kept constant and spike length increases, drag first decreases then increases then decreases [3]. The lengths were studied using the L/b ratio, which refers to the aerospike length versus the blunt-body diameter. For this experiment, researchers tested L/b = 0.4, 0.6, 0.8, 1.0, 1.25, 1.5, 1.875, 2.125. and 2.5 [3]. When L/b is less than 1.0, a large recirculation region occurs in front of the body, whereas when L/b transitions from 1.0 to 1.25, the recirculation region becomes smaller and the strength of the reattachment shock increases [3]. Since the angle of the reattachment point decreases between L/b = 1.0 to L/b =1.25, the amount of the body exposed to the flow before the reattachment point decreases and, thus, the recirculation region decreases, so there is less shielding of the body from the incoming high-speed flow [3]. With L/b = 1.0 as the ideal length of the spike, 65.1% of drag reduction is provided for the foremost portion of the blunt body [3]. Han, Liu, et al. also indicated that the optimal L/b value is 1.0, as the recirculation zone is too small in the earlier values to shield the whole body [11].

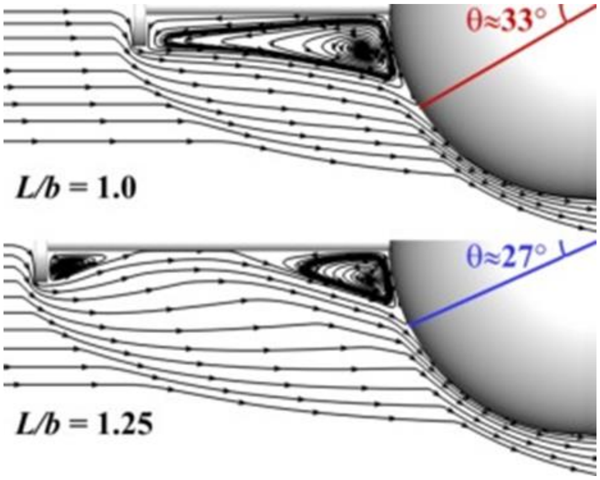
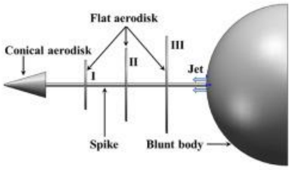


Fig. 3 Effect of spike-length-to-diameter ratio on the recirculation region [3]

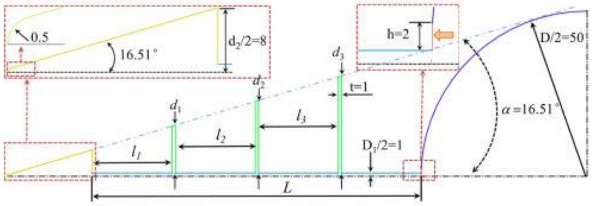
Further, according to Zhao, Shao, and Liu, increasing the L/b from 0.5 to 3.0 in a configuration with three flat aerodisks decreases the drag coefficient by 55.02% [6].

C. Number

A single 30 mm aerodisk attached to a spike with a length equal to the diameter of the blunt body (L/b = 1.0) has a large effect on drag reduction. Using this information, researchers began to experiment with the effects of multiple aerodisks on the blunt body. Zhang, Wu, et al. found that the use of multiple flat aerodisks and a jet gradually lifts the reattachment wave from the main body and lowers its intensity [6]. The study involved the creation of a baseline case in which a conical aerodisk existed at the end of the spike followed by three flat aerodisks and a rear opposing jet: the first flat disk was of a diameter of 30.82 mm, the second flat disk was of a diameter of 45.64 mm, and the third flat disk was of a diameter of 60.48 mm [6]. The distance from the base of the conical aerodisk to the blunt body was 96 mm, and all of the aerodisks were evenly spaced out. Compared to a case with only the spike and conical aerodisk, the drag coefficient for the baseline case decreased by 51.2%, indicating the effect of multiple aerodisks on drag reduction for the blunt body [6]**.**



(a) The geometrical model



(b) Schematic diagram of the geometric dimension

Fig. 4 Baseline configuration of a conical aerodisk, three flat aerodisks, and an opposing jet (not shown) tested [6]

III. Aerodisk Combinations

The aerodisk is often employed in combination with other technologies, including a spike to extend its length and a channel or a jet to further reduce drag. In this way, the flow field can more efficiently be altered for practical applications.

A. With spike

It is known that the length of the spike greatly affects the drag the body experiences [3]. When an aerodisk is attached to the spike, the length of the spike increases slightly and the body experiences less surface pressure distribution [3]. The hypersonic flow forms a bow shock wave in front of the aerodisk and then reattaches to the spike surface; the reattachment wave is weaker than the bow shock wave, which protects the body from the drag from the shock wave [4, 8]. With L/b = 1.0 as the ideal length of the spike, 65.1% of drag reduction is provided for the foremost portion of the blunt body [3].

B. With spike and channel

Ni, Fang, et al. determined a configuration involving a flat aerodisk with a spike connected to a blunt body; the key addition is a channel between the disk and the spike with nozzles surrounding the spike so that high-pressure air can enter the aerodisk and exit through the nozzles in the spike [4].

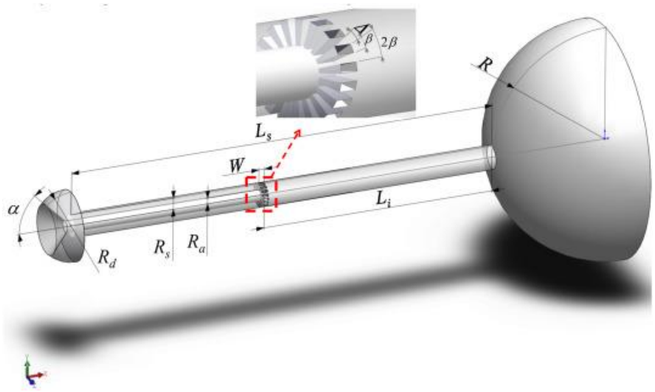
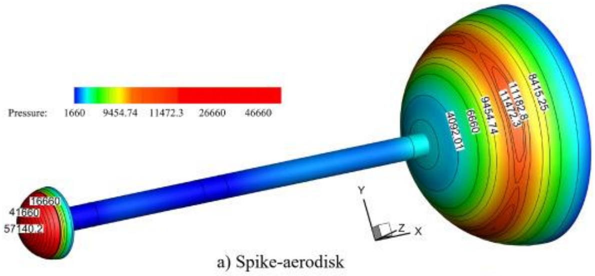
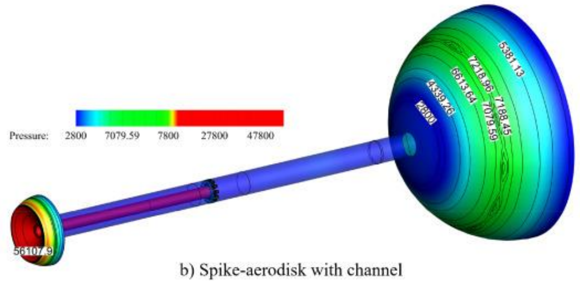


Fig. 5 Aerodisk-spike-channel configuration [4]

Through the use of the spike-aerodisk configuration, the aerodisk experiences the full force of the bow-shock wave at its head and allows for the reattachment shock wave to the body to be an oblique shock wave, therefore reducing the intensity of the shock wave that the body experiences [4]. When the channel is implemented, it serves as, in essence, a jet that allows high-speed air received from the inlet in the aerodisk to exit from the middle of the spike; this allows for the ideal phenomenon in hypersonic speeds for the recirculation region to expand. The addition of the channel reduces the maximum pressure experienced by 43.6%; this decrease in pressure leads to drag reduction [4].



a) Spike-aerodisk



b) Spike-aerodisk with channel

Fig. 6 Differences in pressure contour of spike-aerodisk and spike-aerodisk-channel [4]

According to a study done by Guo, Fang, et al, in the disk-spike-channel model, the blunt body, the disk, and the body as a whole experience a 14.49% decrease in drag from the configuration with a spike-aerodisk [7].

C. With spike and jets

An opposing jet allows for greater ability to push the reattachment shock wave away from the blunt body [6]. Zhang, Xu, et al., in an experiment testing three different models against a baseline model with a conical aerodisk and three flat-aerodisks on a spike and an opposing jet, determined that a model using a conical aerodisk, a spike, and an opposing jet has a drag coefficient only slightly higher than that of the baseline case (with the baseline coefficient being 0.3525 and the aerodisk-spike-jet coefficient being 0.3611) [6]. Compared to the third test case of a conical aerodisk and three flat aerodisks on a spike (but no jet), the drag coefficient for the spike, conical aerodisk, and opposing jet was 0.3611 and the coefficient for the system with three aerodisks was 0.4446, indicating that the jet on its own had more influence in reducing drag than the three flat aerodisks on their own. Out of these four cases, the baseline configuration (which includes the conical aerodisk, spike, three flat aerodisks, and the opposing jet) has the minimum drag coefficient, indicating that the presence of a jet in combination with an aerodisk-aerospike model proves efficient [6].

IV. Comparison of Available Technologies

In general, increasing the length of the spike until the length-to-blunt body diameter ratio reaches 1.0 [3, 11], increasing the diameter of the aerodisk, and including more aerodisks (with caution as to what the diameters are with respect to each other) will increase drag reduction and expand the recirculation region. With these parameters available, multiple combinations can be used that employ them. The aerodisk-with-spike model decreases drag compared to a model without a disk or spike, but adding some sort of channel or jet to the spike would further decrease drag. The channel would allow high-speed air to escape from the spike and act as a jet, and the opposing jet would push the reattachment shock away from the main body. As indicated by Zhang, Xu, et al., the jet in combination with the disk and spike would produce significant drag reduction [6].

Based on these findings, an ideal baseline system can be created with a 30 mm aerodisk attached to a spike whose length is equal to the blunt body's diameter. To expand upon the capabilities of this diameter of aerodisk and this length of spike, a conical aerodisk and two flat aerodisks can be added for a total of four aerodisks. Also, a form of the jet mechanism, either a jet through nozzles in the spike or an opposing jet as indicated by Zhang, Xu, et al. [6] would provide ideal drag reduction.

V. Conclusion

A review of various aerodisk parameters—such as length, diameter, and number—and combinations—such as with a spike, with a spike and channel, and with a spike and an opposing jet—have been surveyed and compared, with findings that increasing aerodisk length, diameter, and number to a certain critical point generally decrease drag and that the inclusion of a jet or a spike with a channel serving as a jet allows for further drag reduction. By exploiting the drag reduction effects of these technologies, a blunt body's flow field can be altered to allow greater capability for hypersonic flight.

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