Numerical study of lateral coolant jet on heat reduction over nose cone with double-aerodome at hypersonic flow

Mehdi Ghanbari, Soroush Maddah & Javad Alinejad

One of the main challenges in designing a supersonic forebody is thermal protection. The application of the mechanical spike mounted at the nose considerably decreases the heat load on the main body. In this investigation, the hybrid technique of mechanical spike and coolant injection are examined to reduce the thermal load on the nose cone in the supersonic air stream. A three-dimensional model of a double aerodisked spike with different cooling systems is provided to find the efficient cooling injection system for reducing the heat load on the nose cone. Computational studies have been done on investigating a cooling mechanism in the proposed injection systems. This study has tried to present valuable information on flow features and shock interaction nearby the nose. The influence of different coolant gas on the thermal performance of the proposed configurations is comprehensively explained. Our results indicate that the cooling performance of single carbon dioxide is 85% more than helium jet in lateral injection. According to our findings, the cooling performance of lateral multi-jets is 90% more than opposing ones.

The importance of hypersonic vehicles is undeniable for humans and scientists who believe the future is a world of fast transportation systems. Indeed, high-speed flight not only enable humans to quick civil flight but also help human to move beyond the earth via shuttle

The flow analyses of the hypersonic vehicles are widely done to disclose the effective factors and parameters associated with aerodynamic heating. Although these studies have presented significant data about the mechanism of the aerodynamic heating around the nose of the cone, there are still some challenges i.e. laminar to turbulence transition, heat reduction technique, and turbulence simulations. Due to production of the excessive heat nearby the nose, the control of the unadorned aerohesing has become a vital challenge for the design of hypersonic vehicles. Meanwhile, drag force is another factor that should be considered for the design of an efficient forebody for the high-speed vehicle. Hence, there are some configurations that are developed for the reduction of aerodynamic heating and drag force. Three main devices have been introduced for the control of aerodynamic heating: mechanical, fluidic, and thermal devices. These techniques have their own pros and cons and these are extensively studied in previously published papers. Among these devices, the mechanical spike is the simplest and most practical technique that is used in real models. Aerodisk spike is known as the most
efficient version of a mechanical device for the reduction of heat load on the main body. Other techniques are developed on a lab scale and investigated in academic studies. Recently, hybrid devices have also become popular since these combined techniques reduce the disadvantage of the main concept and improve the overall efficiency of the forebody at high-speed flight. The mechanical device of the spike has lots of advantages. Since the spike is the most convenient device for real applications, scholars have tried to combine this method as the primary device with the fluidic and thermal approach. A fluidic jet has acceptable efficiency for local cooling and could reduce the temperature of the main body. Thus, we have tried to investigate a new configuration that includes aerodisked spike and fluid device. As demonstrated in Fig. 1, the injection of both single and multi-jets nearby the nose cone with a double aerodisked spike at a hypersonic free stream. The main expected advantage of this model is the heat reduction of air nearby the main body while the drag of the main body is managed via spike with mounted aerodisked. This separation between the heat and drag force mechanism improves the overall performance of the whole model in different conditions.

In this paper, computational fluid dynamics is used to study the hybrid technique of mechanical and fluidic devices simultaneously on the heat and drag reduction mechanism of the nose cone at the hypersonic free stream. Several coolant injection systems are examined on the nose cone with double aerodisk at supersonic flow. Shock interactions and coolant effects on the heat transfer of the nose cone are extensively explained. This study also reveals the impacts of coolant gas (Helium and Carbon dioxide) on the heat rate of the main body. A three-dimensional model is produced to consider the main physic of the main flow and coolant jet. Various jet locations are also compared and the efficient jet configuration is introduced in this work.

Governing equations
To study the compressible flow around the nose cone, RANS equations are coupled with the SST turbulence model to simulate the three-dimensional supersonic flow around the nose cone with a double aerodisk. Since inert gases of helium and carbon dioxide are selected for cooling the nose cone, a species transport equation is also required for the simulation of the proposed configuration. OpenFOAM free code is used for computational simulation of the double aerodisked spike with coolant injections. The second-order upwind scheme of Roe is used to discretize the convective terms. The mixing law is used for the calculation of the heat transfer coefficient in the vicinity of the main blunt-body. In the selected model (Fig. 2), the diameter of the nose cone is 50 mm. The sonic nozzle has a diameter of 4 mm. The length of the spike is equal to the diameter of the nose cone. The supersonic air flow with Mach and static pressure of 5 and 2550 Pa, respectively, at a static temperature of 221 K is applied via pressure far-field boundary condition. Helium and carbon dioxide are injected from different locations at sonic velocity with a total temperature of 300 K. The jet total pressure is about 10% of the total pressure of the free stream. The constant temperature is applied to the body wall. Six jet locations on the nose and spike are investigated in our study. The angles of the injector on the nose cone are 0, 30, and 60°.

A grid study is also performed for the correct simulation of the compressible flow around the nose cone with a double aerodisk. Since the shock is produced nearby the main body and spike, the production of the grid in these regions is done via specific considerations. The size of the grid nearby the nose is lower while the aspect ratio and cell skewness of produced grids are kept in a standard range to avoid divergence. The grid study is also examined with four different grid sizes on two lines (θ = 30 and 60) on the main body as presented in Table 1. Four different grids are examined in this study for the grid independency analysis. It is found that the fine grid is a reasonable grid for our model. 72 h are computational time while our residual become less than 10e−4.

Results and discussion
Validation. To certify the proposed model and obtained results, we must initially compare our results with experimental data. Since experimental data of the simple cone44, we initially simulated the flow characteristic around the nose cone without a spike. Figure 3 demonstrated the velocity profile at a specific location and pressure distribution on the main body for the simple model. The numerical data of Zhu et al.39 is also presented in these figures for the verification of our results. According to our comparison, the deviation of our numerical simulation with experimental data and other computational studies is within an acceptable range. Finite volume technique is extensively used for different engineering problems.
Figure 2. Injection system for cooling of the nose cone with double aerodisked spike.

Table 1. Grid details.

| Model     | Grid number | Average Stanton numb. on blunt cone (θ = 30) | Average Stanton on numb. blunt cone (θ = 60) |
|-----------|-------------|-----------------------------------------------|-----------------------------------------------|
| Coarse grid | 680,000     | 0.00212                                       | 0.00618                                       |
| Normal grid | 960,000     | 0.00245                                       | 0.00637                                       |
| Fine grid  | 1,320,000   | 0.00251                                       | 0.00651                                       |
| Very fine grid | 1,680,000 | 0.00253                                       | 0.00653                                       |

Figure 3. Validation of velocity profile. 

Exp. (Dechaumphai et al.)
Num. (Zhu et al.)
Our Num. data
Flow analysis. In this study, the flow study of the single jet at different locations (3 lateral jets and 3 opposing jets) is fully investigated. 3-D results are also presented to clarify the main impacts of the single jet on flow features and shock interactions nearby the nose body. Then, dual jets (one lateral jet + one opposing jet) are investigated for helium jets. Finally, the existence of three either lateral or opposing jets is fully explored for both helium and carbon dioxide jets. The influence of these jet configurations on the heat load reduction of the main body would be disclosed.

Figure 4 demonstrates the flow feature around the spiked nose cone with double aerodisks in presence of a single opposing coolant jet at the hypersonic free stream. The contour is presented on the plane in the mid-section of the domain. A comparison of the Helium and carbon dioxide indicate that the concentration of the carbon dioxide is higher nearby the nose cone and this is favorable for the cooling system. A comparison of the streamlines shows that the structure of the circulation is preserved by injection of the helium jet since the Helium jet tends to penetrate straightly rather than radially. As the jet injection moves up, the reattachment point moves downstream.

Figure 5 illustrates the mass contour of the single opposing jet of helium and carbon dioxide. Our results indicate that the interaction power of the carbon dioxide coolant jet is more than the helium one. In fact, the high concentration of the carbon dioxide jet in the recirculation region provides a high-pressure region which increases the angle of the shear layer. The three-dimensional feature of the coolant jet indicates the influence of the shock interactions in the vicinity of the jet and shear layer (Fig. 5). The fluctuation of the coolant layer demonstrates the impacts of different jet locations on the flow feature nearby the shoulder of the nose cone.

The impact of the single lateral injections of coolant gas on the flow stream and coolant distribution is demonstrated in Fig. 6. It is found that the injection of the lateral jet increases the number of recirculation nearby the spike. A comparison of the helium and carbon dioxide jet indicates that the helium jet preserves the circulation structure as it is observed in the opposing jet. The existence of a second aerodrome avoids the separation of the circulation on the spiked rod.

Figure 7 demonstrates the jet interactions on the specific plane located on the mid-angle of the domain. The impacts of the lateral helium and carbon dioxide for different jet locations are illustrated. Our comparison indicates that the shock deflection is more clear when the jet location is close to the tip of the first aerodrome (J4). In fact, the gap of the shear layer with bow shock decreases when the coolant jet is injected into the vicinity of the first aerodome. A comparison of helium and carbon dioxide also confirms that the higher penetration of the helium jet is more effective on the deflection of the shear layer. Figure 7 also confirms the role of the helium jet on the flow feature around the forebody in comparison with carbon dioxide.

Figure 8 demonstrates the flow feature of the helium (upper figure) and carbon dioxide jet (lower figure) injected from the tip of the aerodome. Our results indicate that the carbon dioxide jet efficiently disperses the incoming air stream and this deflects the bow shock with a higher angle. Consequently, the attachment point on the main body does not occur on the main body, and the heating of supersonic flow is decreased.

Heat transfer. Figure 9 compares the heat reduction performance of these jet configurations for both helium and carbon dioxide on the main body. As introduced in Fig. 2, jet numbers 1, 2, and 3 are opposing jets while the jet numbers 4, 5 and 6 are lateral jets. Our results indicate that lateral jet injection is more efficient in
heat reduction than opposing jets when carbon dioxide is selected as a coolant. The impact of the helium opposing jet decreases when the jet becomes close to the shoulder of the main blunt body.

Figure 5. Effects of 3-D shock interaction of helium and CO$_2$ opposing jet in different location on the penetration of the coolant jets.

Figure 6. Comparison of helium (left side) and CO$_2$ (right side) lateral jet for different location on the main body.
Conclusion
This study has performed several computational investigations to investigate the impacts of cooling injections on the thermal performance of the spiked nose cone with double aerodomes. The injection of single and multiple coolant jets is fully investigated at the supersonic free stream of $M = 5$. A 3-D model is developed for our investigations to observe real aspects of flow features near the nose cone. Injection of carbon dioxide and helium are compared on the proposed models. Our investigation indicates that, in opposing configuration, helium jet is more efficient for heat reduction in both single and multi-jets. Our results show that the cooling performance of single carbon dioxide is 85% more than helium jet in lateral injection. It is also observed that the helium jet is more efficient than carbon dioxide for the cooling system of the opposing jet.

Figure 7. 3-D feature of the coolant jets (helium and CO$_2$) on the structure of the flow stream nearby the main body.

Figure 8. Comparison of the helium.
Data availability

All data generated or analysed during this study are included in this published article.

Received: 1 August 2022; Accepted: 10 October 2022
Published online: 27 November 2022

References

1. Huang, W. A survey of drag and heat reduction in supersonic flows by a counterflowing jet and its combinations. J. Zhejiang Univ.-Sci. A 16(7), 551–561 (2015).
2. Moradi, R., Mahyari, A., Gerdoodrobdary, M. B., Abdollahi, A. & Amini, Y. Shape effect of cavity flameholder on mixing zone of hydrogen jet at supersonic flow. Int. J. Hydrogen Energy 43(33), 16364–16372 (2018).
3. Pish, F. et al. Computational study of the cavity flow over sharp nose cone in supersonic flow. Int. J. Mod. Phys. C 31(06), 2050079 (2020).
4. Du, M., Yan, L., Huang, W., Li, S. B. & Li, L. Q. Detailed parametric investigations on drag and heat flux reduction induced by a combinational spike and opposing jet concept in hypersonic flows. Int. J. Heat Mass Transf. 126, 10–31 (2018).
5. Huang, W., Du, Z. B., Yan, L. & Xia, Z. X. Supersonic mixing in airbreathing propulsion systems for hypersonic flights. Prog. Aerosp. Sci. 109, 100545 (2019).
6. Gerdoodrobdary, M. B. & Hosseinalipour, S. M. Numerical simulation of hypersonic flow over highly blunted cones with spike. Acta Astronaut. 67(1–2), 180–193 (2010).
7. Gerdoodrobdary, M. B. Aerodynamic Heating in Supersonic and Hypersonic Flows: Advanced Techniques for Drag and Aero-Heating Reduction 1st edn. (Elsevier, 2022).
8. Liu, X. et al. Computational study of the multi hydrogen jets in presence of the upstream step in a Ma = 4 supersonic flow. Int. J. Hydrogen Energy 45(55), 31118–31129 (2020).
9. Barzegar Gerdroodbary, M., Moradi, R. & Babazadeh, H. Computational investigation of multi hydrogen jets at inclined supersonic flow. Int. J. Energy Res. https://doi.org/10.1002/er.5821 (2020).
10. Barzegar Gerdroodbary, M., Mokhtari, M., Fallah, K. & Pourmirzaagha, H. The influence of micro air jets on mixing augmentation of transverse hydrogen jet in supersonic flow. Int. J. Hydrogen Energy 41(47), 22497–22508 (2016).
11. Pish, F., Hassanvand, A., Barzegar Gerdroodbary, M. & Noori, S. Viscous equilibrium analysis of heat transfer on blunted cone at hypersonic flow. Case Stud. Therm. Eng. 14, 100464 (2019).
12. Barzegar Gerdroodbary, M. Numerical analysis on cooling performance of counterflowing jet over aerodisked blunt body. Shock Waves 24(5), 537–543 (2014).
13. Jiang, H., Liu, J., Luo, S. C., Wang, J. Y. & Huang, W. Hypersonic flow control of shock wave/turbulent boundary layer interactions using magnetohydrodynamic plasma actuators. J. Zhejiang Univ.-Sci. A 21(9), 745–760 (2020).
14. Feuzty, D., Badcock, K. J. & Richards, B. E. Driving mechanisms of high-speed unsteady spiked body flows, part 2: Oscillation mode. AIAA J. 42(1), 107–113 (2004).
15. Shen, B. X., Liu, H. P. & Liu, W. Q. Influence of angle of attack on a combined opposing jet and platelet transpiration cooling blunt nose in hypersonic vehicle. J. Zhejiang Univ.-Sci. A 21(9), 761–769 (2020).
16. Liu, X. et al. Effect of strut angle on performance of hydrogen multi-jets inside the cavity at combustion chamber. Int. J. Hydrogen Energy 45(55), 31179–31187 (2020).
17. Barzegar Gerdroodbary, M., Scramjets: Fuel Mixing and Injection Systems 1–220 (Elsevier Ltd., 2020).
18. Edalatpour, A., Hassanvand, A., Barzegar Gerdroodbary, M., Moradi, R. & Amini, Y. Injection of multi hydrogen jets within cavity flameholder at supersonic flow. Int. J. Hydrogen Energy 44(26), 13923–13931 (2019).
19. Hassanvand, A., Barzegar Gerdroodbary, M. & Abazari, A. M. Injection of hydrogen sonic multi-jet on inclined surface at supersonic flow. Int. J. Mod. Phys. C 32(03), 2150043 (2021).
20. Jiang, Y. et al. Effect of cavity back height on mixing efficiency of hydrogen multi-jets at supersonic combustion chamber. Int. J. Hydrogen Energy https://doi.org/10.1016/j.ijhydene.2020.07.001 (2020).
21. Sun, C., Gerdroodbary, M. B., Abazari, A. M., Hosseini, S. & Li, Z. Mixing efficiency of hydrogen multijet through backward-facing steps at supersonic flow. Int. J. Hydrogen Energy 46(29), 16075–16085 (2021).

22. Liu, X. et al. Numerical simulation of the hydrogen mixing in downstream of lobe strut at supersonic flow. Int. J. Hydrogen Energy https://doi.org/10.1016/j.ijhydene.2020.06.130 (2020).

23. Hassanvand, A., Saei Moghaddam, M. Barzegar Gerdroodbary, M. & Amini, Y. Analytical study of heat and mass transfer in axisymmetric unsteady flow by ADM. J. Comput. Appl. Mech. Eng. 11(1), 151–163 (2021).

24. Jang, Y. et al. Effect of free stream angle on mixing performance of hydrogen multi-jets in supersonic combustion chamber. Int. J. Hydrogen Energy https://doi.org/10.1016/j.ijhydene.2020.06.055 (2020).

25. Amini, Y. & Nasr Esfahany, M. CFD simulation of the structured packings: A review. Sep. Sci. Technol. 54(15), 2536–2554 (2019).

26. Zhang, Y., Gerdroodbary, M. B., Hosseini, S., Abazari, A. M. & Li, Z. Effect of hybrid coaxial air and hydrogen jets on fuel mixing at supersonic crossflow. Int. J. Hydrogen Energy 6(29), 16048–16062 (2021).

27. Li, Z. et al. The influence of the wedge shock generator on the vortex structure within the trapezoidal cavity at supersonic flow. Aeros. Sci. Technol. 98, 105695 (2020).

28. Li, Z. et al. Mixing enhancement of multi hydrogen jets through the cavity flameholder with extended pylon. Acta Astronaut. 175, 300–307 (2020).

29. Pish, F., Moradi, R., Edalatpour, A. & Gerdroodbary, M. B. The effect of coolant injection from the tip of spike on aerodynamic heating of nose cone at supersonic flow. Acta Astronaut. 154, 52–60 (2019).

30. Qin, Q. & Xu, J. Numerical evaluation of aerodynamic and cooling jet for aeroheating reduction. Aeros. Sci. Technol. 86, 520–533 (2019).

31. Moradi, R., Mosavat, M., Gerdroodbary, M. B., Abdollahi, A. & Amini, Y. The influence of coolant jet direction on heat reduction on the nose cone with Aerodome at supersonic flow. Acta Astronaut. 151, 487–493 (2018).

32. Qin, Q., Xu, J. & Guo, S. Fluid–thermal analysis of aerodynamic heating over spiked blunt body configurations. Acta Astronaut. 132, 230–242 (2017).

33. Zhang, Y., Gerdroodbary, M. B., Moradi, R. & Babazadeh, H. Influence of the sinusoidal shock generator on the mixing rate of multi hydrogen jets at supersonic flow. Aeros. Sci. Technol. 96, 105579 (2020).

34. Li, Z. et al. Influence of upstream strut on hydrogen fuel distribution inside the supersonic combustion chamber. Int. J. Hydrogen Energy https://doi.org/10.1016/j.ijhydene.2020.06.026 (2020).

35. Li, Z. et al. Numerical simulation of the hydrogen mixing in downstream of lobe strut at supersonic flow. Chin. J. Aeronaut. 32(4), 771–784 (2019).

36. Xuwan, S. U., Huang, W., Min, O. U., Zhang, R. & Shiban, L. I. A survey on numerical simulations of drag and heat reduction mechanism in supersonic/hypersonic flows. Chin. J. Aeronaut. 32(4), 771–784 (2019).

37. Hassanvand, A., Saei Moghaddam, M. Barzegar Gerdroodbary, M. & Amini, Y. Analytical study of heat and mass transfer in cavity flameholder at supersonic flow. Chin. J. Aeronaut. 32(4), 771–784 (2019).

38. Li, Z. et al. Effect of multi hydrogen jets on mixing performance of hydrogen in cavity flameholder at supersonic flow. Acta Astronaut. 43(20), 9829–9837 (2018).

39. Li, Z., Gerdroodbary, M. B., Moradi, R., Manh, T. D. & Babazadeh, H. Effect of inclined block on fuel mixing of multi hydrogen jets in scramjet engine. Acta Astronaut. 105, 106035 (2020).

40. Menter, F. R. Two-equation eddy-viscosity turbulence models for engineering applications. Prog. Aerosp. Sci. 105, 31–39 (2019).

41. Manh, T. D., Nam, N. D., Gerdroodbary, M. B., Babazadeh, H. & Moradi, R. Numerical simulation of mixing of hydrogen jet at supersonic cross flow in presence of upstream wavy wall. Int. J. Hydrogen Energy 45(1), 1096–1106 (2020).

42. Li, Y. Gerdroodbary, M. B., Moradi, R. & Babazadeh, H. The influence of the sinusoidal shock generator on the mixing rate of multi hydrogen jets at supersonic flow. Aeros. Sci. Technol. 96, 105579 (2020).

43. Jang, Y. et al. Effect of dual micro fuel jets on mixing performance of hydrogen in cavity flameholder at supersonic flow. Int. J. Hydrogen Energy https://doi.org/10.1016/j.ijhydene.2020.06.130 (2020).

44. Hassanvand, A., Gerdroodbary, M. B., Fallah, K. & Moradi, R. Effect of dual micro fuel jets on mixing performance of hydrogen in cavity flameholder at supersonic flow. Sci. Rep. 12(1), 1–12 (2022).

45. Jang, Y. et al. Theoretical study of MHD electro-osmotically flow of third-grade fluid in micro channel. Appl. Math. Comput. 420, 126868. https://doi.org/10.1016/j.amc.2021.126868 (2022).

46. Chu, Y.-M. et al. Combined impact of Cattaneo–Christov double diffusion and radiative heat flux on bio-convective flow of Maxwell liquid confined by a stretched nano–material surface. Appl. Math. Comput. 419, 126883. https://doi.org/10.1016/j.amc.2021.126883 (2022).

47. Zhao, T.-H., Ijaz Khan, M. & Chu, Y.-M. Artificial neural networking (ANN) analysis for heat and entropy generation in flow of non-Newtonian fluid between two rotating disks. Math. Methods Appl. Sci. https://doi.org/10.1002/mma.7310 (2021).

48. Isanejad, M. & Fallah, K. Numerical study of droplet breakup in an asymmetric T-junction microchannel with different cross-section ratios. Int. J. Mod. Phys. C 33(10), 2250023 (2022).

**Author contributions**

M.G. wrote he main manuscript text S.M. and J.A. prepared figures. All authors reviewed the manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

Correspondence and requests for materials should be addressed to S.M.

Reprints and permissions information is available at [www.nature.com/reprints](http://www.nature.com/reprints).
Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2022