Jesse Groves

AE 525 Literature Review

Review of effusion cooling methods as active thermal protection systems for hypersonic vehicles

Abstract: The increased need for hypersonic vehicles is becoming more and more apparent in the world today. From delivering payloads to commercial transportation, lower traveling times are becoming increasingly more important, but there are a few challenges that must be addressed before these goals of widespread hypersonic transportation are met. Due to the extremely high heat transfer rates at high Mach numbers, active cooling methods are import in keeping payloads safe and hypersonic systems functional during flight for extended periods of time. One method currently being studied is effusion, or the injection of a coolant inside the boundary layer through micro holes cut into the surface of the body. This paper will present a review of the literature covering previous work done on effusion and other similar cooling techniques. This includes different types of coolants, coolant flow rates, effusion hole placements, and the effects these have on heat transfer rates.

I. Introduction

A hypersonic vehicle is defined as a vehicle that travels at Mach 5 (or five times the speed of sound) or faster. These vehicles are becoming increasingly popular, but traveling at these speeds brings many complex challenges that must be dealt with before take-off for successful missions is possible. For a blunt nose cone of a hypersonic vehicle, an estimated 1.4×10^7 W/m^2 is transferred to the stagnation point at the front of the nose for speeds of around Mach 6 [3], [6]. This type of heat transfer can push surface temperatures up above 2000 K, which is higher than the softening temperature for many materials used in hypersonic vehicles. This means that without some type of cooling system, the parts of the vehicle experiencing these heat transfers could melt, become disfigured, and ultimately fail or become incapable of being reused for future projects. Similarly for other projects, space shuttles, missiles, rockets, and other airbreathing hypersonic vehicles all must be able to withstand extremely high temperatures from this heat transfer.

II. Methods

There are a few methods used in cooling vehicles moving at high speeds, and they can be split into two main categories: active thermal protection systems and passive thermal protective systems. Passive systems are the systems that do not involve any work once they are set in place on the vehicle. Examples of a passive system would be the material chosen for a vehicle that could withstand the temperatures required or designing a blunt nose cone rather than a sharp nose cone to minimize heat transfer at the front of the vehicle. Active cooling methods are similar to passive ones in that the shape of the vehicle and the material used must still be taken into consideration, but there is a second part of the process in which some form of coolant is used to lower the temperature of the material or reduce the heat transfer put upon the material. One type of active thermal protection systems is gaseous cooling film methods. These include film cooling, effusion cooling, and transpiration cooling.

a) Film Cooling

Film cooling is the process of injecting a stream of cold gas into the boundary layer through a small slot on the surface of the wall and is most effective at cooling the surface downstream of the slot due to the build-up of coolant in the boundary layer [4]. Fig. 1 depicts the set up for an experiment done by Cary and Hefner in 1972 at the NASA Langley Research Center in Hampton, VA in which the effects of film cooling in hypersonic vehicles were tested to determine if film cooling could be an effective method of preventing heat transfer [2]. Until this point, transpiration cooling was widely believed to be the most effective and efficient at preventing heat transfer on the surface of a hypersonic vehicle. Film cooling was found to be much less effective, but all the testing was done at Mach numbers of 3 or less, and the data were extrapolated to determine how effective film cooling would be at higher Mach numbers. However, the study done by Carey and Hefner at a Mach 6 tunnel found that the data did not match the expected results of cooling the surface; rather it exceeded these expectations, and the film cooling method produced similar values at these high speeds to transpiration cooling [2].

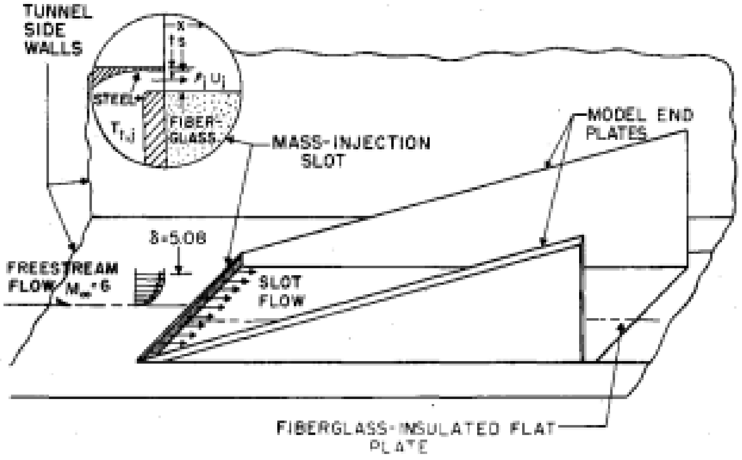

Fig. 1. Shows the setup for the experiment conducted by [2]. This image was received from [2].

b) Transpiration Cooling

Transpiration cooling is known for being the most efficient method for cooling the surface of aerospace vehicles traveling at high speeds [10]. This type of cooling uses a porous material as the wall of the structure and pushes out the coolant through the material. This method is one of the most effective because the coolant travels through the material, and thus has more time to absorb some of the heat that is being transferred onto the body of the vehicle and covers more of the surface area which helps evenly distribute the coolant over the body.

c) Effusion Cooling

Effusion cooling is the process of pushing coolant through micro holes drilled into the surface of the material. Effusion is very similar to transpiration and film cooling in that as the air is pushed through the material, it creates a coolant layer inside the boundary layer that can help prevent heat transfer onto the material at high speeds. Effusion was also considered less efficient than transpiration for the body of hypersonic vehicles, but the studies that showed this were done on bodies at lower Mach numbers. More recent testing of these values at higher Mach number shows that effusion can accomplish similar results as transpiration for protecting the surface temperature [2]. Outside of hypersonics, effusion could be the future in many parts inside turbojet engines like the fan blades and the combustion liners. This is because effusion allows for lighter and less expensive materials to be used along with those materials to be used under more extreme conditions [2].

III. Effusion Optimization

For practical hypersonic use, it is important to cool the surface enough to protect the payload and keep the vehicle functional while also using a practical amount of coolant. For any film cooling, the effectiveness of the film layer at cooling the surface increases as the mass flow rate of the coolant increases. This means that using more coolant will generally protect the surface from heat transfer better. However, there must be enough coolant to last the entire length of the mission, so it is important to optimize coolant flow to allow for enough coolant to last for as long as the vehicle is traveling at hypersonic speeds.

There are a few ways to optimize the mass flow rate of coolant for effusion. First, in a study done by [5] and [10] it was found that less coolant is required downstream of the stagnation region due to coolant build-up. As the coolant exits the holes and enters the boundary layer, it expands and travels in the direction of the incoming air. As the coolant rushes back, it is met with more coolant from the next hole, and so on, causing a build up of coolant. This build-up makes the boundary layer expand and protects the surface from heat transfer. A study done by [10] was completed and to attempted to show that the hole array of effusion holes could be optimized. The results of the experiment, while incomplete, showed that a more dense array of holes at the leading edge of a flat plate and a less dense array of holes towards the trailing edge of the flat plate allowed for a more optimum coolant flow and kept the temperature gradient across the plate much more even compared to a uniform array of effusion holes. This means less coolant is wasted cooling off the middle and end of the plate which do not need as much coolant as the leading edge.

Another parameter to consider in effusion cooling is what gas the coolant is comprised of. In a study conducted by [4], the effects of film cooling on supersonic flow over a flat plate were studied to find ideal ways to use the coolant. Of the different coolants tested, it was found that hydrogen, the least dense gas of each coolant tested, had the best results. As explained by [4], as the coolant exits the perforations, it expands rapidly due to the sudden drop in pressure. This allows for the coolant to cover a larger area and thus protect a larger area from heat transfer. However, this is not perfectly true for stagnation points. Research done by [1] and [8] show that a slightly more dense coolant is beneficial for the stagnation point because higher heat transfer rates occur in these regions and a thicker layer of coolant is more optimal in protecting the surface in the stagnation region.

IV. Applications

a) Engines

Effusion is regarded as one of the most ideal methods of cooling combustor liners of aerospace vehicles [5] and is thought to be the future of gas turbine blade cooling [10] because of the extreme angular velocity of the blades at to produce high thrust. As engines become more complicated, burn hotter, and create more compression, it is important that the engines can handle these pressures and temperatures put on them to keep them from failing during a flight. Hypersonic vehicles have the same issues in that burning the fuels hotter and creating higher overall pressure ratios will make the vehicle faster. Effusion in this part of the hypersonic vehicle keeps the materials surrounding the combustion area from melting, thus allowing the combustion chamber to burn hotter and create more thrust to go faster.

b) Hypersonic Nose cones

One practical application effusion is being used for is to cool the nose cone of hypersonic vehicles. The leading edge of a hypersonic vehicle will experience a very large amount of heat transfer, and one solution to this is to make the leading edge blunt. This makes the shock wave a bow shock and drastically reduces the amount of heat transfer that happens on the surface. This creates much lower surface temperatures, but they are still too high for the materials to handle. So, a film coolant layer can be used at the surface to keep the temperature from weakening or melting the surface. A numerical study by [1] and a similar experimental study done by [8] compared the effects of effusion at the tip of a hypersonic nose cone with a Mach number of 5.9 for a single jet of coolant and an array of smaller jets of coolant. Each study compared different types of coolant, different pressure ratios at which to release the coolant (which determines the mass flow rate of the coolant), and different gases to be used as the coolant. The results of each study showed that the array of closely spaced micro-jets performed much better than the single jet of equivalent area. Sriram and Jagadeesh also showed that with the single jet, there was a stagnation region that appeared around the jet at the surface. This caused a reattachment area that drastically increased the heat transfer rate surrounding the jet shown as the dead air region and the reattachment point in Fig. 2**.** Because not much air is exiting the dead air region, not much coolant is flowing under the reattachment point causing a spike in heat transfer at that point on the surface [8].

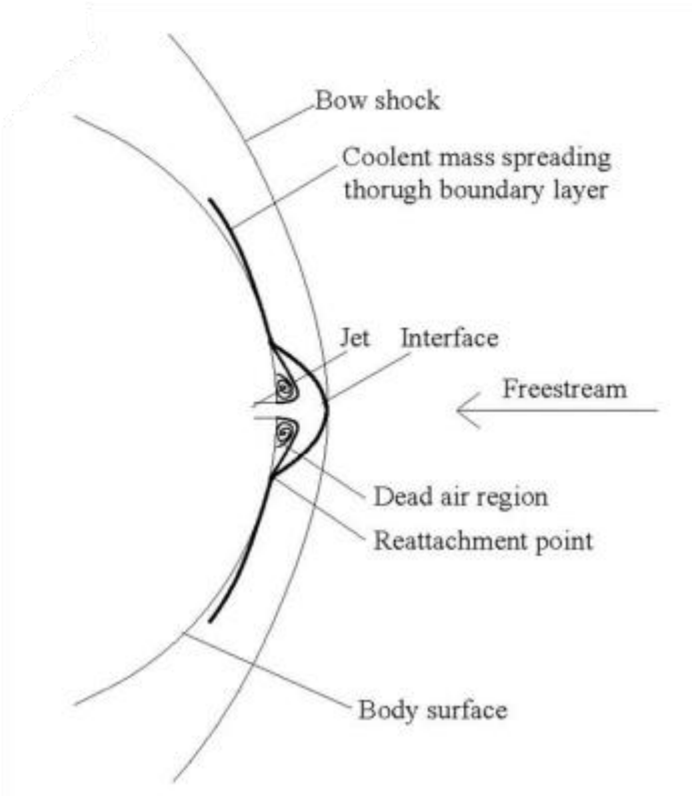

Fig. 2. Shows a single jet of coolant emitted from the front of a blunt nose cone and its effect on the incoming freestream flow.

An array of microjets solves this problem because the smaller holes push the same amount of coolant out as the single jet, but they have less momentum, and thus the air dissipates closer to the surface and creates a smaller dead air region. This minimizes the reattachment area's heat transfer on the body and creates a more efficient system to keep the surface cool.

c) Drawbacks

Each of the three methods of cooling materials mentioned previously have strengths and parts that could be improved. Film cooling is designed to cool downstream of the insertion point and is therefore not an ideal way to cool the stagnation point of a nose cone. For transpiration, it can be difficult to target specific areas with coolant, and if one area needs more coolant than another, it is difficult to direct the coolant to a specific spot (however, research is being done by [9] on non-uniform transpiration cooling). Lastly, for effusion, the density of the coolant plays a large role in how well the coolant works, and different densities are more ideal for different parts of the flow, as discussed previously. This means that each coolant method has inefficiencies and parts where a different method of cooling could be more suited to protect the surface from the incoming flow.

V. Joint Cooling Methods

With the inefficiencies of each method, a solution for creating better thermal protection systems could be to combine parts of each method to cover where the others are less effective. One example of this is research done by [7]. Shen, Yin, Zhang, and Liu studied the effects of a single jet of coolant at the stagnation point of a blunt nose cone for a hypersonic vehicle with a platelet capable of transpiration that surrounds the jet of coolant. The study compared a single jet of coolant with the jet surrounded by the platelet. Similar to [1] and [8], Shen, Yin, Zhang, and Liu found that there was a region of air that circulated just outside the single jet. The transpiration platelet next to this jet of coolant was able to effectively reduce the heat transfer rates caused by reattachment of the shock without using much extra coolant. This resulted in a more effective thermal protection system and used less coolant than would be needed without the transpiration platelet.

VI. Future Work

Future work for effusion is still needed to determine its best applications and how to best optimize the process. This includes finding optimal arrays for effusion holes on different shapes that maximize coolant effectiveness but minimize coolant flow rate, finding the best types of coolant to use in different situations, and further research on film cooling compared to transpiration cooling for high Mach numbers.

Other beneficial work would be to further research the combination of active cooling methods. For example, possibly using two different coolants at different points on hypersonic bodies. As shown by [1], nitrogen worked better than helium as the coolant at the stagnation point of a hypersonic nose cone due to its slightly higher molecular weight, but helium worked better than hydrogen on the other parts of surface due to its slightly lower molecular weight. Another possibility could be to further study the effects of a non-uniform array of effusion holes for hypersonic nose cones. This research would be similar to the work done by [10] and the work done by [9] in that it would use a non-uniform array to maximize the coolant effectiveness while minimizing coolant flow rate.

This would take the effectiveness of the non-uniform coolant flow observed by both [9] and [10] but could more easily be manufactured for testing than [9] which was not able to effectively get the highest flow rate at the stagnation point and the lowest flow rate towards the end of the wedge as intended.

V11. Conclusion

Active cooling is the crucial next step advancing hypersonic vehicles. This paper covered a basic background of necessary principles that must be considered when designing effusion thermal protection systems as well as other notable film cooling methods that could be used together with effusion to create an optimal and effective thermal protection system. Some notable conclusions made are that a high mass flow rate of coolant is more beneficial for preventing heat transfer in hypersonic vehicles, but this mass flow rate should be optimized for plausible long-range missions. The type of coolant must also be taken into consideration. More research comparing different types of coolant is necessary, but it was found that nitrogen was the best of the gas coolants tested for preventing heat transfer at the stagnation point of a blunt nose cone, while helium (or preferably hydrogen when safe to use) provided the best protection of the gases tested on the other regions of the body.

VIII. References

[1] Barzegar Gerdroodbary, M., Imani, M. and Ganji, D., 2015. Investigation of film cooling on nose cone by a forward facing array of micro-jets in Hypersonic flow. *International Communications in Heat and Mass Transfer*, [online] 64, pp.42-49. Available at: <http://www.elsevier.com/locate/ichmt> [Accessed 19 November 2021].

[2] Cary, A. and Hefner, J., 1972. Film-Cooling Effectiveness and Skin Friction in Hypersonic Turbulent Flow. *AIAA Journal*, [online] 10(9), pp.1188-1193. Available at: <http://aiaa.org> [Accessed 13 November 2021].

[3] Huang, Z., Xiong, Y., Liu, Y., Jiang, P. and Zhu, Y., 2015. Experimental investigation of full-coverage effusion cooling through perforated flat plates. *Applied Thermal Engineering*, [online] 76, pp.76-85. Available at: <http://www.elsevier.com/locate/apthermeng> [Accessed 19 November 2021].

[4] Keller, M., Kloker, M. and Olivier, H., 2015. Influence of Cooling-Gas Properties on Film-Cooling Effectiveness in Supersonic Flow. *Journal of Spacecraft and Rockets*, [online] 52(5), pp.1443-1455. Available at: <http://www.aiaa.org> [Accessed 26 November 2021].

[5] Qu, L., Zhang, J., Tan, X. and Wang, M., 2017. Numerical investigation on adiabatic film cooling effectiveness and heat transfer coefficient for effusion cooling over a transverse corrugated surface. *Chinese Journal of Aeronautics*, [online] 30(2), pp.677-684. Available at: <http://www.sciencedirect.com> [Accessed 14 November 2021].

[6] Sahoo, N., Kulkarni, V., Saravanan, S., Jagadeesh, G. and Reddy, K., 2005. Film cooling effectiveness on a large angle blunt cone flying at hypersonic speed. *Physics of Fluids*, [online] 17(3), p.036102. Available at: <http://www.publishing.aip.org> [Accessed 24 November 2021].

[7] Shen, B., Yin, L., Zhang, X. and Liu, W., 2019. Investigation on cooling effect with a combinational opposing jet and platelet transpiration concept in hypersonic flow. *Aerospace Science and Technology*, [online] 85, pp.399-408. Available at: <http://www.elsevier.com/locate/aescte> [Accessed 27 November 2021].

[8] Sriram, R. and Jagadeesh, G., 2009. Film cooling at hypersonic Mach numbers using forward facing array of micro-jets. *International Journal of Heat and Mass Transfer*, [online] 52(15-16), pp.3654-3664. Available at: <http://www.elsevier.com/locate/ijhmt> [Accessed 24 November 2021].

[9] Wu, N., Wang, J., He, F., Chen, L. and Ai, B., 2018. Optimization transpiration cooling of nose cone with non-uniform permeability. *International Journal of Heat and Mass Transfer*, [online] 127, pp.882-891. Available at: <http://www.elsevier.com/locate/ijhmt> [Accessed 28 November 2021].

[10] Yang, L., Dai, W., Rao, Y. and Chyu, M., 2019. Optimization of the hole distribution of an effusively cooled surface facing non-uniform incoming temperature using deep learning approaches. *International Journal of Heat and Mass Transfer*, [online] 145, p.118749. Available at: <http://www.sciencedirect.com> [Accessed 27 November 2021].