Arc Jet Ground Testing for Hypersonic Vehicles and Spacecraft

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This paper analyzes state-of-the-art arc jet wind tunnels within hypersonic ground testing in correlation to the testing and certification of thermal protection systems for hypersonic vehicles and spacecraft. Hypersonic flight is characterized by a variety of phenomena that challenge the design and qualification of airframes, propulsion systems, and especially thermal protection systems for vehicles moving through and reentering the atmosphere of a planet. Arc jet wind tunnels, in either pulsed or continuous operation, provide near-realistic flight conditions and thermal loads, mimicking those that aircraft would experience in flight. Despite the high operating costs of these facilities, arc jet ground testing demonstrates itself to be a more efficient option for the testing and qualification of hypersonic vehicles when compared to in-flight testing. In this paper, I will provide an overview of current hypersonic ground testing facilities, arc jet wind tunnels, the University of Tennessee High-Enthalpy Tunnel, and current and future research applications that arc jet facilities support for the future of hypersonic flight vehicles and spacecraft, specifically with regards to the development of thermal protection systems for the designated vehicles.

I. Introduction

Crewed space flight and aviation have resulted from multiple technological revolutions in the aerospace engineering field and various scientific communities. Programs ranging from SpaceX's Falcon 9 and Crew Dragon to NASA's Space Shuttle have pushed past pre-existing boundaries that have limited humanity's exploration of Earth, the solar system, and beyond. However, while various factors in the aerospace engineering field and scientific communities can be credited for these successes, hypersonic research and developing ground testing facilities for high-temperature testing have been instrumental in redefining the current expectations for hypersonic flight vehicles and spacecraft. Specifically, arc jet wind tunnels and their near modeling of hypersonic environmental conditions have allowed for the development of innovative thermal protection systems to protect vehicles from the high thermal loads established by hypersonic environments. This paper will cover the history of hypersonic research that has enabled the development of arc jet ground testing facilities, the operation and design of arc jet wind tunnels with correlation to the University of Tennessee High-Enthalpy Tunnel, as well the current and future research applications arc jet wind tunnels have on the design of thermal protection systems for the next generation of flight vehicles capable of withstanding hypersonic flight conditions.

II. History of Hypersonic Ground Testing

Hypersonic conditions are defined by the portion of a vehicle's flight that travels above the Mach 5 speed threshold [1]. Above this threshold and below Mach 10, hypersonic flight can be defined in the low hypersonic regime, while the high hypersonic regime is considered above Mach 10. Typically, aircraft in hypersonic flight are analyzed in the low hypersonic regime, whereas spacecraft reentering a planet's atmosphere are placed into the high hypersonic regime during deceleration from orbital speeds. In both regimes, significant environmental and airflow factors associated with hypersonic flight clearly distinguish them from transonic and supersonic flight and have reason to explore their principal nature. This is especially seen in the compressibility of air and the shockwaves surrounding the vehicle that cause a significant increase in air temperature that is then transferred to the vehicle [2]. These high thermal

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loads raise several design challenges regarding protecting the vehicle from extremely high temperatures and maintaining flight stability from various shockwaves and surrounding turbulent airflow while in flight.

Replicating hypersonic flight is extremely difficult to achieve and is the primary focus of many aerothermodynamic research groups worldwide. High airflow speed, lack of facilities capable of hypersonic testing, and mimicking in-flight temperatures have severely hindered research into both the design of vehicles and materials capable of hypersonic flight. The cost of developing such vehicles and performing in-flight testing is also much higher than being able to conduct ground testing for smaller-scale portions of the vehicle regularly. Often, test vehicles are flown aboard aircraft and deployed at high altitudes to significantly cut fuel storage costs and the duration of active propulsion systems. However, there is still a high cost of measuring hypersonic conditions in flight on a fully developed test vehicle capable of failing rather than conducting ground testing on smaller-scale portions of the vehicle. Several developments in hypersonic ground testing have enabled significant cost reductions in the annual expense of vehicles, as well as advancements in establishing ground test facilities that can create conditions a vehicle would experience as part of hypersonic flight. Wind tunnels, in general, have historically been of the blow-down variety in which air accelerates from subsonic to supersonic speeds through a nozzle from a high to low-pressure volume [3]. Long-duration hypersonic tunnels, pulse-shock tunnels, arc jet facilities, and many other ground testing facilities have developed from the foundation of blow-down wind tunnels to allow for more applicable hypersonic research into the environmental conditions and phenomena in flight [4]. Arc jet facilities aim to replicate hypersonic airflow and thermal loads for materials used in hypersonic vehicles and flight conditions like pressure and temperature [5].

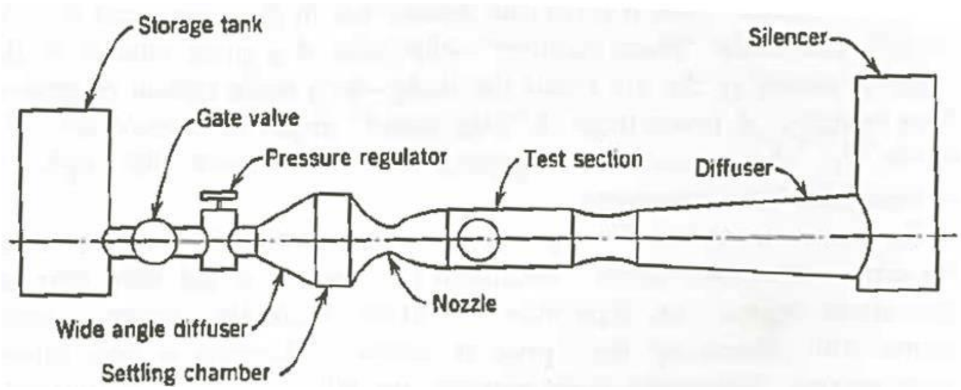

Fig. 1 General Schematic of a Blow Down Wind Tunnel [6].

III. Arc Jet Facilities

Arc jet wind tunnels are advanced hypersonic ground testing facilities that can perform high airflow and thermal testing for aerothermodynamic and materials research that will be used to develop thermal protection systems for vehicles and spacecraft. Thermal protection systems are critical for a vehicle in hypersonic flight as they protect the vehicle and its subsystems from high thermal loads sustained from plasma buildup. This plasma is created from the friction between the vehicle and the atmosphere, where air undergoes molecular dissociation and ionization, causing it to form on the vehicle at very high temperatures [7]. Arc jet wind tunnels aim to model the airflow across a material or the air that enters the test section at high enough temperatures and flow speeds to simulate the thermal loads and atmospheric conditions that a vehicle or spacecraft would experience during flight. These types of hypersonic ground testing facilities are exceptionally accurate in simulating airflow temperature in the hypersonic speed regime by adding an electrical arc that heats the surrounding flowing air before entering the nozzle and then the test section. Since velocity increases and pressure decreases from the inlet and exit of the nozzle, the arc heater portion of an arc jet tunnel aims to rapidly heat the air so that the resulting temperature of the flow exiting the nozzle is modeled to in-flight hypersonic conditions. The tunnels primarily consist of an area where an electrical discharge can occur, a cathode and anode to establish an electrical discharge through an electric potential difference, and a nozzle. Specifically, a converging-diverging nozzle accelerates airflow from the subsonic regime to the hypersonic speed regime [8]. While there are several other elements to arc jet wind tunnels, these are the primary components that allow for high air temperatures and airflow speeds that exit the nozzle and enter the test section to be measured.

Generally, air heating occurs by establishing an electrical arc between the cathode and anode at a set electric potential difference, which can vary in magnitude for testing requirements. Nitrogen and oxygen, used to resemble Earth’s atmosphere, are injected and swirled into the system. To allow for the travel of the air mixture through the tunnel that initially starts at a high pressure stored in a tank that is fed to the system. A vacuum system establishes a near-zero pressure at the end of the tunnel to ensure a maximum pressure difference. The air then flows through the electric arc that heats it and increases its enthalpy before reaching a plenum chamber. The plenum chamber allows for thermal equilibrium in the flow and ensures that the high temperature of the air is not only concentrated in the middle of the flow, which is in direct contact with the electrical arc. After passing through the chamber, it then flows through a converging-diverging nozzle in which the air accelerates to the hypersonic speed regime at various speeds that depend on a variety of factors, including the size of the nozzle and the initial airflow speed into the nozzle. The test section is directly after the nozzle, which allows for various diagnostic equipment and materials being tested for thermal protection systems to have direct exposure to the high-temperature airflow that exits the nozzle and generates plasma. While arc heaters across the country have the same basic operating principle, there are primarily two versions of arc heaters used in arc jet wind tunnels. One of them is a segmented arc heater, and the other is a Huels arc heater, each with unique characteristics [9].

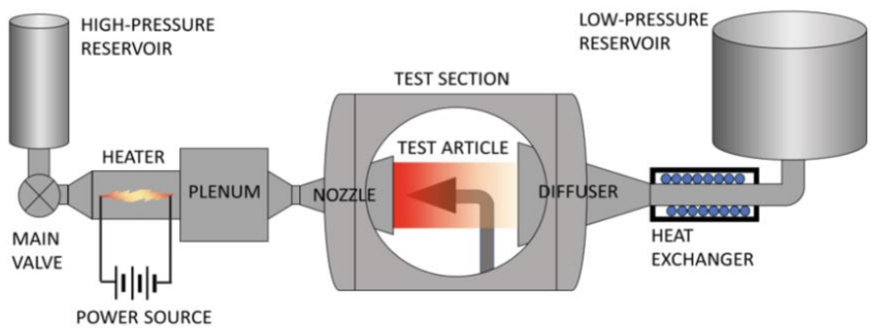

Fig. 2 Arc Jet Wind Tunnel General Schematic [5].

A. Segmented Arc Heaters

A segmented arc heater's primary difference from a Huels arc heater is in the design and implementation of an insulator in the volume of the tunnel that contains the electrical arc between the cathode and anode. In a segmented arc heater, multiple insulators in series with one another separate the cathode and anode [9]. A longer separation between the cathode and anode allows for a longer arc to be established and, therefore, an increase in enthalpy for the gas flowing through the tunnel. The segmented arc heaters also allow for the design of more segments, typically copper plates, to be added to the heater portion of the tunnel to set a distance in which the arc attaches [10]. This allows for less ablation of the copper into the flow and, therefore, less contamination in the chemical composition of the flow exiting the nozzle to the test section by having a set point of attachment of the arc on the anode and stabilization due to the low temperatures surrounding the inner walls of the heater [14]. Typically, segmented arc heaters can produce enthalpy levels in the range of 2,000 to 12,000 Btu/lbm (4.65 to 27.9 MJ/kg) between 1 and 10 MPa, with some facilities having the capability of above 100 MPa [8]. These facilities have a greater chance of repeatable test conditions due to relatively fixed arc lengths between the electrodes, and relatively near equal amounts of enthalpy inputted into the airflow.

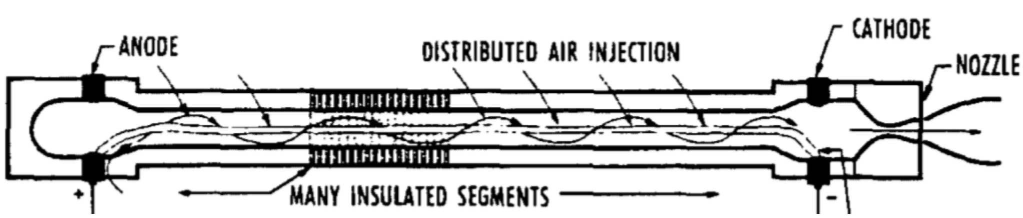

Fig 3. Segmented Arc Heater Schematic [11].

B. Huels Arc Heaters

A Huels arc heater is an arc jet heater with only one primary insulator. In this case, the arc attachment is spontaneous and is never in a set location when it attaches to the electrode. With a varying arc attachment, there is then a differing length of air that can be heated by the arc, limiting the increase in enthalpy of the air. However, Huels arc heaters are very low maintenance and prevent less ablation and damage to the cathode, as shown in Fig. 4, from the arc attachment repeatedly selecting a single area of the electrode it can attach to. This provides more uniform damage to the electrode, potentially significantly cutting operating and maintenance costs, rather than repeatedly replacing the electrode from test to test. Test conditions between each test are less repeatable because the length varies between electrodes, as often there will be a difference in the arc length established within the heater. Therefore, Huels arc heaters, when compared to segmented arc heaters, will have a lower enthalpy range produced and is in the range from 1,500 to 4,000 Btu/lbm at pressures up to 16.7 MPa [8].

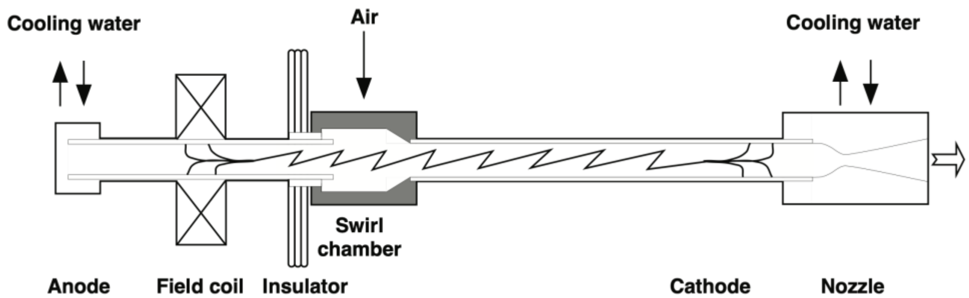

Fig. 4 Huels Arc Heater Schematic [6].

For testing purposes, arc jet heaters can either be run in pulsed or continuous operational modes and can control the time the electrical arc is established in the heater and how long air is flowing through to the test section. The pulsed operational mode only allows a short amount of time, in milliseconds to a few seconds, in which airflow and arc attachment are permitted. This allows for relatively low temperatures in the equipment used on the arc jet tunnel and does not require continuous cooling of the system. Pulsed operations can also be used for diagnostic purposes in which instrumentation is used to analyze the flow exiting the nozzle in short durations, rather than needing a full-duration test. Continuous operation modes for arc jet tunnels differ significantly from a pulsed operation mode, in which a cooling system is required to ensure the temperature load of the containment boundary of the tunnel does not reach high enough temperatures to melt. Often, this is a costly addition and requires significant additions to a preexisting tunnel to ensure adequate cooling. However, by allowing for longer test durations of upwards of a minute, hypersonic flight conditions can be easily simulated to the duration of flight that a vehicle and spacecraft will experience.

IV. The University of Tennessee High-Enthalpy Tunnel

The University of Tennessee High-Enthalpy Tunnel (Tenn-HET) is a pulsed arc jet wind tunnel that was developed from a segmented and Huels arc jet configuration, with a power capability of running in either pulsed or continuous mode at 260 kW or 500 kW, respectively. Tenn-HET has the same operational principle as other arc jet facilities by establishing an electrical arc to heat air that flows through a plenum chamber to achieve relative thermal equilibrium that then moves through a converging/diverging nozzle to accelerate airflow to a relative Mach number in the hypersonic regime. The tunnel uses a ceramic insulator for the interior portion of the arc heater, with an auxiliary and primary anode located within the chamber for the arc attachment from the cathode [5]. After air flows out of the nozzle and past an array of sensors, primarily a variety of pressure and temperature gauges, it moves through a heat exchanger to cool the airflow and enters a vacuum, low-pressure system. For the system startup procedure, argon is used as an initial gas to help achieve an electrical arc attachment to the auxiliary anode. Once the arc attaches to the auxiliary anode, the arc can achieve a full arc attachment to the primary anode in which there is a brief overlay where the arc attaches to both anodes before a switch opens, cutting off the auxiliary anode. The control valve is then shut off for the argon supply, and depending on operational tests, valves can be opened for nitrogen and oxygen to simulate atmospheric airflow, where mass flow rates can easily be controlled. This procedure happens in a relatively low amount of time, ranging in milliseconds, to allow most of the test time to be dedicated to airflow testing once the arc achieves stable attachment and has very little downtime between tests.

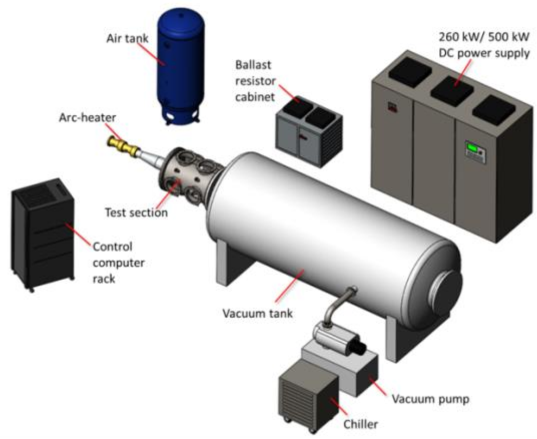

Fig. 5 Tenn-HET Facility Layout [5].

Current hypersonic and aerothermodynamic research at Tenn-HET has primarily focused on the measurement and characterization of the facility's average stagnation enthalpy value from the airflow leaving the nozzle, as well as the measured Mach number, pressure, and temperature values of the airflow [12,13]. With a maximum voltage of 1,000 volts and 500 amps in pulsed operation, as shown in Fig. 7, the tunnel test envelope can replicate enthalpy values up to 16 MJ/kg and airflow speeds of Mach 6 and greater [5]. Currently, work is being completed on the spectroscopic characterization of the airflow entering the test section with the measurement of chemical byproducts of the airflow from a variety of mixtures of nitrogen and oxygen. The data from these experiments and measurements will aid various research into hypersonic flow, specifically for developing materials capable of handling the high thermal loads on vehicles from hypersonic flight. This will aid in the design and implementation of thermal protection systems that can withstand hypersonic and atmospheric reentry conditions for hypersonic vehicles and spacecraft.

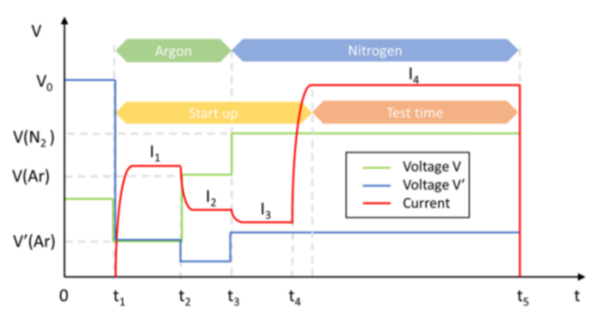

Fig. 6 Voltage and current as a function of time for Tenn-HET arc jet tunnel [12].

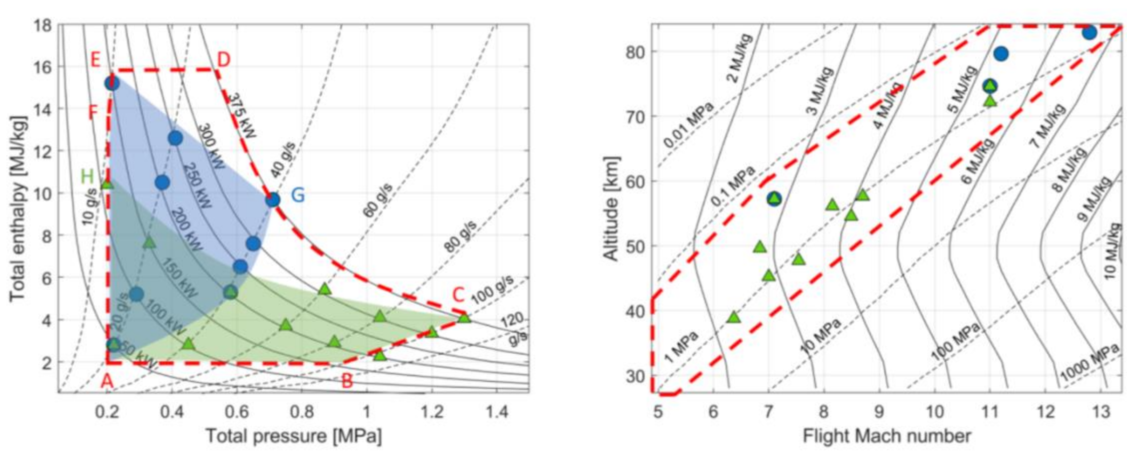

Fig. 7 Pressure, enthalpy, Mach number, and altitude replication capabilities of Tenn-HET [5].

To enable a continuous operational mode to allow for the full duration of material testing in hypersonic flight conditions and measurement of hypersonic flight conditions, Tenn-HET will implement a water-cooling system in the facility to allow for longer duration testing of the tunnel. This also includes improving the low-pressure reservoir system to enable a maximum pressure difference for the flow to travel through while implementing a diffuser to collect the airflow at the end of the test section.

V. Current and Future Research Applications

Arc jet facilities have been used worldwide in aiding the development of society's understanding of hypersonic flight and the phenomena that occur when a vehicle spacecraft moves at hypersonic speeds. With temperature ranges of 3,000 K up to 10,000 K, arc jet facilities have the primary capability of performing high-temperature testing for materials that will be used to protect vital systems aboard hypersonic vehicles and spacecraft [15]. Currently, these facilities have been the testing grounds for thermal protection systems as well as carbon composite materials that are used in a variety of hypersonic vehicles and heat shields on spacecraft to protect the vehicles from the buildup of plasma that occurs from friction in hypersonic flight [16]. These materials, such as Zirconium Diboride (ZiB2) and Silicon Carbide (SiC), will often ablate away from the vehicle at slow rates from the rapid heating of hypersonic environments as a form of cooling to ensure the underneath layers of the heat shields and the coating of vehicles will withstand the high-temperature loads.

Another increasingly important area of research for which arc jet facilities are being used is the testing and development of scramjet engines on hypersonic vehicles from the fuel-to-air mixtures in hypersonic flow that arc jet facilities can produce [17]. Scramjet engines allow air to be "rammed" into the combustor portion of the vehicle and allow for supersonic combustion, which then flows from the combustor to a nozzle [18]. Since Earth's atmosphere is primarily composed of nitrogen and oxygen, researchers are analyzing and developing techniques that maximize the fuel-to-air ratio's maximal optimization to allow for maximum thrust efficiency in combustion between the fuel and air. Arc jet facilities provide similar airflow speeds and a replication of thermal air that other hypersonic wind tunnels do not provide in evaluating and designing hypersonic propulsion systems. This research would allow for the rapid development of next-generation hypersonic propulsion systems that would transform current hypersonic vehicles and their ability to maintain hypersonic flight.

VI. Conclusion

Hypersonic flight has become an increasingly important area of research across the world, where there has been a high demand for the testing and qualification of hypersonic systems and thermal protection systems for hypersonic vehicles and spacecraft. Arc jet facilities have demonstrated themselves to be ideal testing facilities in the replication of thermal and plasma loads that are associated with hypersonic flight, as well as replicating hypersonic airflow speeds. Between pulsed and continuous operation modes, as well as segmented and Heels arc jet facilities, hypersonic aerothermodynamic research has been accelerated and transformed from the long history and variety of testing capabilities that arc jets provide, with the potential and testing envelope of Mach 6 speeds and greater and airflow and plasma enthalpies ranging up to 25 MJ/kg. For humanity to continue exploring the depths of space, revolutionizing commercial air travel, and improving national security on Earth, arc jet facilities play a pivotal role in developing society's understanding of hypersonic flight and the phenomena that occur within flight and atmospheric reentry of Earth and beyond.

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