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Arcjets and Arc Heaters: An Overview of Research Status and Needs

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Arcjets and arc heaters are important to a number of government-sponsored aerospace programs and share several common features. Placing satellites in orbit, maintaining proper orbit, and repositioning are major spacecraft mass drivers for a wide range of missions. Arcjets can reduce mission propulsion requirements in many cases and are of interest to many satellite users. Arc heaters are critical to the future development of hypersonic combat aircraft. Design and construction of a hypersonic aircraft for speeds of 4–5 km/s (Mach 12–15) will be complex and will require the development of high-performance arc-heating facilities for the evaluation/validation of new airframe and propulsion technologies. The first objective of this overview is to provide a summary of the basic principles of arcjets and arc heaters for readers unfamiliar with the field. The second objective is to describe fundamental research required to overcome the limitations of both devices, with an emphasis on common research areas. This overview is not comprehensive, but does include national research and development activities. It is intended as a guide to the organization of scientific research serving both arcjet and arc-heater development communities.

Nomenclature

A = cross-sectional area
A^* = throat area
F = thrust
g = gravitational constant
h = freestream enthalpy
h_t = stagnation enthalpy
I_{sp} = specific impulse
M = Mach number
m = mass flow rate
$m_{payload}$ = payload mass
m_0 = initial mass
P = input power
p = freestream pressure
p_t = stagnation pressure
R = gas constant
s = entropy
T = freestream temperature
T_t = stagnation temperature
u_e = exhaust velocity
ΔV = velocity change
η = thruster efficiency
γ = specific heat ratio
ρ = freestream density
ρ_t = stagnation density

Subscript
t = stagnation conditions

Introduction

ARCJETS and arc heaters utilize an arc generated between electrodes to heat a working fluid to extremely high temperatures. The working fluid is injected and passed through the arc before being exhausted through a nozzle at one end of the device. Arcjets typically employ a constricted design (see Fig. 1) in which the arc initiates at the tip of a cathode, extends through the constrictor (throat), and attaches in the diverging section of the nozzle, which also serves as the anode. Depending on propellant type and operating conditions, arcjets can provide exhaust velocities from 5000 to 13,000 m/s. This range of velocities is significantly higher than that attainable with state-of-practice (SOP) chemical propulsion systems. Thus, substitution of arcjet systems could result in significant propellant savings in multiple mission applications (see, e.g., Ref. 1). Major technical issues affecting arcjet development are called out in Fig. 1 and center on increasing efficiency, stability, and life. Arc heaters typically produce high-temperature gas streams by passing cold air through an electric discharge established between the electrodes in the arc chamber, as shown in Fig. 2.[2] High-temperature gas then exits through a nozzle at desired velocity, enthalpy, and density combinations. Electric arc heaters are used extensively to heat air to temperatures in the range of 10,000 K for the extended periods required for testing of both airframe structures and materials and scramjet engines. Major technical issues affecting arc-heater development are operational reliability (erosion/life and stability) and flow quality (e.g., purity, uniformity, and stead-

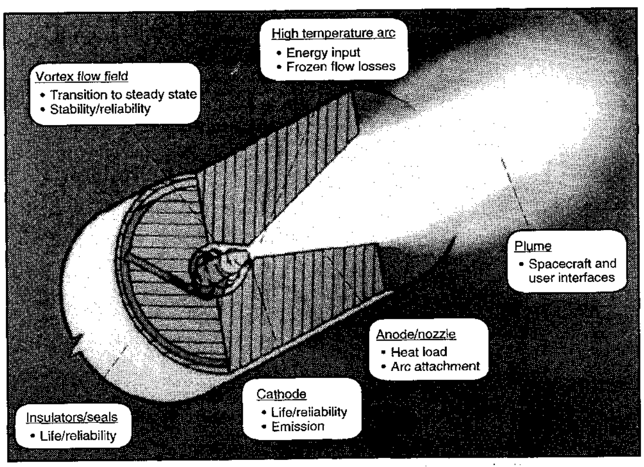

Fig. 1 Schematic of a constricted arcjet with call outs of major technical issues.

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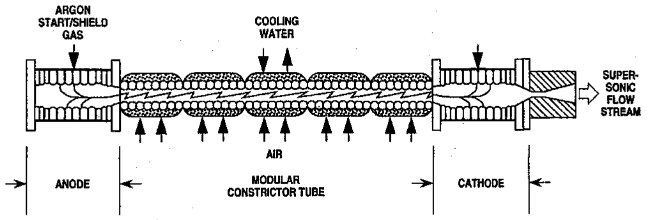

Fig. 2 Typical segmented arc heater (from Ref. 2).

iness). Even though operational regimes and designs are different for arcjets and arc heaters, the performance and lifetime of both devices can be advanced through a better understanding of nonequilibrium processes, arc stability, and electrode attachment/erosion. Nonequilibrium processes impact dissociation, ionization, recombination, vibrational, rotational, and electronic excitation, and radiative nonequilibrium, and so are important to overall energy transfer/distribution. These processes also affect electrode mass loss in arc heaters as they play a large role in determining the thermal environment in the near-electrode region. Electrode materials and processes set fundamental limits on the operating envelopes of the devices. Arc instabilities can cause severe damage to both arcjets and arc heaters if fluctuations in the operating mode (e.g., attachment point) result in unacceptable heat-flux levels to critical surfaces. In arcjets, both electromagnetic and electrothermal instabilities may be responsible for arc fluctuations and unsteady anode attachments. In arc heaters, hydrodynamic instabilities may also cause arc oscillations.

Significant efforts have been expended in the development of both arcjets and arc heaters to date. To realize the full potential of these devices, advances in the fundamental understanding of plasma processes and arc/electrode interactions will be required. This article provides first a brief background on arcjets and arc heaters and then a discussion of some ongoing research in the area.

Background

Arcjets

Electric propulsion devices can be categorized as electromagnetic, electrostatic, or electrothermal. A summary of electric propulsion utilization in operational and experimental flights are given in Table 1.[6] Arcjets fall into the electrothermal category and, as noted earlier, utilize an arc to heat the propellant to high velocities with respect to SOP chemical systems. Arcjets and arcjet propulsion systems have been described by numerous authors.[3–6]

Arcjets have been proposed for a variety of mission applications. These applications include stationkeeping, low- to mid-ΔV orbital insertions, orbital maneuvering, primary propulsion for small space–science spacecraft, and large-scale orbit transfers [e.g., low Earth orbit (LEO) to geosynchronous Earth orbit (GEO)]. Considerations involving space storability and compatibility with existing spacecraft systems make storable liquids such as hydrazine or ammonia the propellants of choice for all but the high-ΔV orbit transfer missions. An example of the benefits that can be derived from arcjet application is provided by the kilowatt-class devices now being used for North–South stationkeeping (NSSK) on several geosynchronous commercial communications satellites (GEO comsats). In the early 1980s, GEO comsat NSSK was performed using small chemical or resistojet thrusters with I_{sp} of about 300 s, and satellite lifetime was limited by the available NSSK propellant. Both SOP systems were at/near theoretical performance limits. Kilowatt-class arcjets with I_{sp} projected at 1.5–2 times SOP were targeted for development by a government/industry team. The successful first application of arcjet technology (for NSSK) significantly reduced required launch mass and led to an international launch vehicle competition. Arcjets have since been used to greatly increase satellite life. Details of the kilowatt-class arcjet development program were recently reviewed by Curran and Byers.[4] There is currently a broad national trend toward developing smaller satellites (250 kg or less), which are significantly cheaper, and quicker to produce, deploy, and operate. Substantial miniaturization of electronic components during the past 15 years has both enabled and encouraged this trend. These small satellites are also often power-limited and have significant ΔV requirements for orbit transfer and control. Low-power arcjets may offer a simple, cost-effective option for these missions and a joint government/industry development program is in progress.[7]

Operating parameters of greatest interest in electric propulsion systems are exhaust velocity (commonly expressed in terms of specific impulse), thrust, input electric power, propellant mass flow rate, and thruster efficiency. The relationship among these quantities can be written as

$$\eta = TI_{sp}g/2P \tag{1}$$

where

$$T = mu_e \tag{2}$$

$$I_{sp} = u_e/g \tag{3}$$

Another critical parameter for the electric propulsion system is the total impulse I_t available per system. This, along with the total impulse required to perform a selected mission and specified redundancy considerations, sets the total number of thrusters required for the missions. Required thruster/system lifetime can then be determined from practical considerations. If high-power hydrogen arcjets are ever to be used for ambitious orbit transfer missions, I_{sp} (with demonstrated lifetime) must be increased and time to orbit (given realistic power constraints) must be reduced. Specific impulse drives propellant requirements and, because the fuel of choice is hydrogen, increased I_{sp} is perhaps more important from the standpoint of volume than mass. While increased specific impulse can be attained by operating at high specific power settings, operating in this range adversely affects thruster lifetime and efficiency (and so, system complexity, reliability, and time to orbit at a given power level). Time to orbit is a key for user acceptance in both commercial and government sectors. To reduce trip time, thruster efficiency must be increased over demonstrated levels. Hydrogen arcjet orbit transfer systems have recently been designed,[6,8] and recent studies indicate that arcjets must achieve 1300 s specific impulse with a thruster efficiency above 40% to be considered over other alternatives.[6] These performance parameters have not been demonstrated, and it is anticipated that extensive research and development efforts will be required to achieve these goals.

Arc Heaters

Hypersonic testing requirements for propulsion materials and structures dictate the need for high pressures and temperatures not attainable by conventional means. High-pressure arc facilities have historically been used to simulate very steep intercontinental-ballistic-missile re-entry trajectories. Low-pressure, high-enthalpy arc heaters are utilized to simulate shallow re-entry such as the Space Shuttle trajectory. Materials and structures testing requires matching of the static pressure and the total enthalpy without concern for its distribution between static and kinetic energy. Propulsion testing requires matching of many parameters including, for example, combustor static pressure, the combustor inlet Mach number, gas composition, and total enthalpy. In addition to the simulation parameters discussed earlier, the simulation for both material and propulsion testing may also be affected by the flow uni-

Table 1 Summary of experimental and operational electric propulsion flights[6]

Country	Before 1980 Thruster type (mission/year)	After 1980 Thruster type (mission/year)
United States		
Commercial		52 hydrazine resistojet (GS/80)
		>75 hydrazine resistojet (GS/83)
		4 hydrazine arcjet (GS/93)
Air Force	4 Teflon® pulsed plasma (GS/68)	
	2 nitrogen resistojet (OA/65)	
	12 nitrogen resistojet (OA/67)	
	1 cesium ion (SD/65)	
Navy	10 ammonia resistojet (OA/65)	
	8 ammonia resistojet (OA/71)	
	10 Teflon pulsed plasma (OA/76)	
	1 hydrazine resistojet (SD/71)	
NASA	2 cesium ion (PE/74)	
	4 ammonia resistojet (SD/67)	
	4 ammonia resistojet (SD/69)	
	2 mercury ion (SD/70)	
USSR	6 Teflon pulsed plasma (AC/64)	40 SPT-70 (GS/82)
	12 SPT-50 (OA/74)	12 SPT-70 (AC/87)
	1 Xe SPT, 1-Hg ion (SD/71)	4 Xe SPT (GS/93)
	1 potassium MPD (PE/75)	2 cesium arcjet (PE/80)
Japan	2 ammonia MPD (SD/79)	4 Xe ion (GS/94)
		2 mercury ion (SD/82)
		1 Ar MPD (PE/83)
		4 Teflon pulsed plasma (PE/81)
		1 hydrazine MPD (PE/94)
Europe		1 Xe ion (SD/92)

AC, attitude control; GS, geosynchronous stationkeeping; and OA, orbit adjustment (used in operational flights). SD, subsystem demonstrations and PE, plume and environmental studies (used in experimental flights).

formity, flow purity, unsteadiness, boundary-layer effects, and the injection/main flow interactions that can be summarized as flow quality.[9] Summaries of the major arc facilities throughout the world used for aerospace applications are given in Tables 2 and 3 for chamber pressures above and below atmospheric, respectively.[2]

A typical arc-heater test arrangement consists of an arc chamber, which acts as a pressure and enthalpy reservoir, a convergent–divergent nozzle to give uniform, shock-free flow at the desired speed, a diffuser, and an exhaust plant. There are many types of arc heaters designed to accomplish specific simulations based on how arc discharge is stabilized within the arc chamber: vortex-stabilized by strong gas swirl, wall-stabilized segmented-type by installing many water-cooled insulated disks, magnetically-stabilized by rotating arc attachment, and magnetoplasmadynamic generator using hot tungsten cathode for arc control.[2]

One-dimensional, isentropic, ideal gas flow theory can be used to describe the test section flow conditions that are found to be a good approximation to many actual flows. Nozzle flow properties such as temperature, pressure, density, velocity, and area ratio can be calculated as a function of Mach number once arc chamber p_t and h_t are specified. It follows from the isentropic flow assumption that[10]

$$(T/T_t) = (p/p_t)^{(\gamma-1)} = (\rho/\rho_t)^{(\gamma-1)/\gamma} = \{1 + [(\gamma - 1)M^2/2]\}^{-1} \quad (4)$$

γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume. M is a dimensionless flow quantity and is defined as the ratio of the flow velocity to the acoustic velocity:

$$M = u/a \quad (5)$$

where acoustic velocity is defined for an ideal gas

$$a^2 = \left(\frac{\delta p}{\delta \rho}\right)_s = \gamma RT \quad (6)$$

which is independent of pressure.

The ratio of A to A^* can be calculated from the continuity equation as

$$A/A^* = M^{-1}([2/(\gamma + 1)]\{1 + [(\gamma - 1)/2]M^2\})(\gamma + 1)/2(\gamma - 1) \quad (7)$$

where sonic conditions are attained at the throat for an equilibrium supersonic flow.

It follows from the previous equations that the local enthalpy at the test section can be calculated as a function of Mach number

$$h = h_t - (u^2/2) = h_t - 0.5\gamma RT_t(M^2/\{1 + [(\gamma - 1)/2]M^2\}) \quad (8)$$

which is the difference between stagnation enthalpy and kinetic energy. Theoretical studies have been conducted to plot equilibrium airflow properties for stagnation pressures up to 1000 bar and stagnation enthalpies up to 56,987 kJ/kg.[11] These assumptions give predicted results that are within a few percent of the experimental results for many flows. As an example, a Mach 12, 0.47-bar dynamic pressure scramjet simulation requires 0.55-bar static pressure, a Mach number of 3.8, and a total enthalpy of 7 kJ/kg, which, in turn, implies an arc chamber pressure of 100 bars.

It is desirable to push the simulation up toward Mach 15, but this requires a chamber pressure considerably above the current limits. Flow quality issues are always of concern, but stringency of the requirements depends on the type of testing being done. A discussion of arc-heater flow quality as it relates to hypersonic testing is included in Ref. 12.

Research Status and Needs

The following sections are intended to provide the reader with an overview of recent progress in the areas of arcjet and arc heater development and to identify several key research areas for the future.

Experimental studies have been conducted to understand physical processes occurring in arcjet thrusters and much of this data has been used to anchor/validate recent computational

Table 2 Arc-heater facilities operating over 1 bar

Country	Operation year	Maximum power, MW	Maximum pressure, bar	Maximum enthalpy, kJ/kg	Exhaust	Mech nr. range, M	Test size diameter ($L \times H$), cm (cm × cm)
United States							
AEDC	77	30	120	13,920	Atmospheric	1.8–3.5	2.8–7.6[a]
	83	42	100	9280	Atmospheric	1.8–3.2	2.8–10.2[a]
	89	42	100	9280	SA[b]	4.5–8.3	22.9–106.7[a]
	95?	60	150	13,920	Atmospheric	2.0–3.7	5.1–11.4
	70	20	40	32,480	SA	2.5–12	30.5 to 106.7[a]
NASA Ames Research Center	71	20	20	9280	SA	–3.5	(20.3 × 50.8)
	72	20	10	32,480	SA	–3.5	(35.6 × 35.6)
	74	60	10	46,400	SA	3.5–7.5	(61 × 61)
	92	100	25	9280	SA	–3.1	?
NASA Johnson Space Center	66/2	10	10	37,120	SA	3–5.5	(61 × 61)
NASA Langley Research Center	——	12	40	8120	SA	4.7–7	(28 × 28)
McDonnell Douglas Aerospace	68	10	250	13,920	Atmospheric	1.7–3	5.1[a] (2 × 3.3)
	74	10	100	13,920	SA	–8	61[a]
Aeroterm Co.	85	1.2	30	116,000	Atmospheric/SA	0.3–6	12[a] (2.54 × 10.2)
University of Texas	94	1.6	20	9280	SA	?	?
Russia							
Central Research Institute	——	40	6	9280	SA	–6	(60 × 100)
	——	50	50	9280	SA	0.5–2.5	5.8[a] (50 × 15)
	——	10	80	9280	SA	0.5–6	5.1[a] (19.8 × 30)
	——	5	50	46,400	SA	–2	19.3[a]
Central Aerohydrodynamics Institute	——	80	160	3120	SA	10–20.5	99[a]
	——	40	100	5800	SA	1–9	35[a]
	——	1	10	9280	SA	4–8	(3 × 17.8)
	——	6	200	9280	SA	7–20	30[a]
	82[c]	1	180	49,880	SA	8–15	19.8[a]
France	79	20	60	13,224	Atmospheric	1.7–2.4	(19.8 × 3)
	87	9	130	5104	Atmospheric	–3.6	0.8[a]
	87	5	15	13,920	SA	–5	(30 × 30)
	92	20	10	18,096	Atmospheric	–2.1	13[a]
Germany	89	1	14	25,520	SA	3.3–5.7	28
	94	6	40	34,800	SA	3.3–5.7	28
Israel	85	5	30	39,440	Atmospheric/SA	2.2–5	36[a]
Italy	96?	70	17.6	39,904	SA	4.8–5.3	(60 × 60)
Japan	61	0.1	1.2	12,992	SA	——	6.6[a]
	93	0.75	1.1	30,160	SA	——	(17.3 × 2)
	94	0.5	22	19,952	SA	–5.5	11[a]

[a]Cylindrical maximum test sample diameter. [b]Subatmospheric. [c]Arc-driven magnetohydrodynamic facility.

Table 3 Arc facilities operating under 1 bar

Country	Type	Operation year	Maximum power, MW	Maximum pressure, bar	Maximum enthalpy, kJ/kg	Gas flow speed, mm/s	Test size diameter ($L \times H$), cm (cm × cm)
United States							
NASA Langley Research Center		——	1	1	34,800	——	——
USSR							
Central Research Institute	MPD[a] accelerator	——	4	<0.1	46,400	0.98×10^4	(400 × 160)
	440-Hz plasmatron	——	1.5	<0.4	46,400	1.97×10^3	(19.8 × 0.91)
Central Aerohydrodynamics Institute	Induction heating	——	0.24	0.4	37,120	4.11×10^3	18.6[b]
	Induction heating	——	1	0.8	37,120	4.11×10^3	4[b]
Germany	Plasma wind	87	0.25	1	116,000	1.61×10^4	——
	Plasma wind	90	1	0.5	150,800	1.61×10^4	——
Japan	Plasma jet	64	0.015	1	12,992	——	(2 × 5)
	Plasma wind	65	0.03	0.006	200	——	5.5[b]
	MPD[a] accelerator	71	5	0.1	49,880	——	6[b]
	Plasma wind	73	0.005	1	3000	——	2.7[b]
	Erosion test	92	0.02	1	——	——	(5 × 5)

[a]Magnetoplasmadynamics. [b]Cylindrical maximum test sample diameter.

models. Diagnostic techniques to measure the fundamental properties of arcjet plasma flows have been detailed in several recent articles.[13–17] Langmuir probes have been used extensively to investigate arcjet plumes.[13–15] Plume properties are of great interest to spacecraft integrators and both experimental characterization and modeling efforts undertaken in the recent past were critical to the final selection of arcjets for spacecraft application. For example, langmuir probe data taken by both Zana and Sankovic[13,14] were used in conjunction with a model[18] to show that the electrical characteristics of the plume did not adversely impact communications in typical geosynchronous communications satellite applications. Keefer et al.[16] measured axial and radial velocities simultaneously in an ammonia arcjet plume using two multiplexed laser beams to monitor both hydrogen Balmer alpha and atomic nitrogen lines. Current modulation velocimetry, a time-of-flight technique in which a current spike induces optical emissions that are measured in two axial locations, has been used to provide instantaneous average velocities of the arcjet plasma with temporal resolution of a few microseconds.[17]

Internal flow and component characterizations are complicated by both the harsh environment and small dimensions of typical arcjets. The characteristics of these flows and components, however, control operational behavior, life, and performance of these devices to a large extent. Because of this, much emphasis has recently been placed on the development of both intrusive and nonintrusive diagnostics techniques measuring cathode conditions, static pressure, temperature, and plasma density, as well as densities and velocities throughout the interior region of the arcjet thruster extending to the exit plane. Cappelli and Storm[19] have reviewed past and recent experimental techniques to measure internal flow properties of arcjet thrusters. Zube and Myers[20] used emission spectroscopy to characterize internal flows. Static pressure measurements were performed to obtain information about internal flowfield characteristics, and losses associated with viscous effects.[21] Current attachment at the anode, floating potential, and anode fall voltage were investigated using a segmented-anode approach,[22] and arc–cathode interactions have been studied by a variety of methods.[23] Arc heaters are usually characterized by measuring gross operational parameters such as power input, heat loss, mass flow, and efficiency. In addition to these basic operating parameters, the effluent is routinely probed to characterize it as a test medium. Few detailed measurements inside the arc heater have been taken to diagnose internal plasma flow properties. The diagnostics being developed for the arcjet should be equally applicable to probing arc-heater internal characteristics.

While much progress has been made in the experimental characterization of arcjets, this has been slow to translate into optimized devices. This is, in part, because experimental data do not always provide clear insight into optimization processes. Also, experimental research is expensive and time consuming. An accurate predictive model of arc phenomena would be the ultimate tool for rapid, cost-effective arcjet design with a minimum of in-laboratory testing, and several extensive plasma flow modeling efforts have been undertaken in the recent past. In general, discrepancies between code outputs and experimental data are common to date and it is clear that a better understanding of flow and electrode physics will be required for the development of an accurate code (and ultimately, a fully optimized arcjet). At present, inadequacy in the understanding of 1) nonequilibrium processes, 2) arc instabilities, and 3) arc/electrode attachment regions is thought to be of greatest importance, and these areas are examined in the following sections.

Nonequilibrium Processes

To date, the arcjets models have been found to consistently overpredict performance (e.g., I_{sp} and efficiency) when model outputs are compared with experimental arcjet data. This observation suggests that significant energy losses have been neglected by simplifying assumptions about thermal and chemical equilibrium. For example, Spores et al.[17] measured atomic hydrogen ground state densities, velocities, and temperatures near the arcjet nozzle using a two-photon laser-induced fluorescence, and found that continuum models[23,24] underpredict atomic hydrogen density by an order of magnitude. The transport properties used in these models, especially the electric conductivity, are very sensitive to nonequilibrium processes and inaccuracies in the estimation of these properties could lead to the observed discrepancies. Boyd et al.[25] used a direct simulation Monte Carlo technique that modeled the flow on a molecular level to improve agreement with the experimental results. Further work will be required, however, to fully describe the flow and include treatments of electrode-related phenomena. In arc heaters operating at high pressures (i.e., ~100 bar), the bulk of the flow is in equilibrium at high pressures, and so can be described by standard continuum codes. This is not the case at lower pressures, however, and description of the flows in these devices will require treatments similar to those used for the arcjet. Nonequilibriun analysis will be required for near-electrode region at all pressures in both devices.[26]

Ionization, dissociation, and recombination processes must all be considered in describing plasma flows and chemical nonequilibrium may occur when the finite rate kinetics controlling the flow properties are not fast with respect to the time scales inherent to the device. This can lead to local temperatures, densities, etc., significantly different than those that would be observed at equilibrium. These differences, in turn, impact gross transport properties. A simplified example of chemical nonequilibrium in hydrogen flow has been discussed by Keefer et al.[16] To better describe nonequilibrium flows, models that account for finite rate kinetics of important species must be developed.

Thermal nonequilibrium is usually caused by large differences in masses between particles (e.g., electrons and ions). Two-temperature models have recently been used in models by both Megli et al.[24] and Miller and Martinez-Sanchez[27] to account for thermal nonequilibrium. The presence of molecular species in a plasma may give rise to non-Maxwellian or non-Boltzmann electron energy distributions in the plasma and this, in turn, may suggest that multienergy models, rather than multitemperature models, would be appropriate in some cases.

Internal-mode nonequilibrium (e.g., vibrational, rotational, and electronic excitation) is governed by processes whose characteristic times are on the order of the local convective time scale and may couple to the other type of nonequilibrium processes in discharge. Internal-mode nonequilibrium can occur over a wide range of pressures in the gas phase. Some models and measured rates for energy transfer via vibration–vibration, vibration–translation, and vibration–electronic modes are available.[28–36] Babu et al.[28] discuss an internal-mode nonequilibrium model consisting of a total energy equation, electron energy distribution function, and the rate equations that govern the number densities of various species.

Arc-heater codes include radiation transfer, using a diffusion model.[37] This is probably adequate for high-pressure operations, but may not be adequate for the arcjet where the optical depths are similar to constrictor dimensions, especially in the upstream region. Gogel et al.[38] used Monte Carlo techniques to describe this regime in arcjets.

Experiments also discovered that common nozzle geometries lead to an underexpanded exhaust flow.[16] Zube and Myers[20] found that the electron number density in the nozzle is a strong function of the nozzle geometry. In addition, electron number densities and temperatures drop significantly along the nozzle, which, in turn, implies inefficient translational energy exchange. It was also found through optical measurements that constrictor flow was far removed from ionizational equilibrium, with the plasma significantly over dense with respect to Saha equilibrium.[20,39]

Arc/Electrode Attachment

An understanding of the detailed physics of the discharge in the immediate region around the attachment to the electrode surfaces, where there is a rapid transition from gaseous to solid-state conduction of electrical current, is key to understanding such issues as arc behavior upon initiation and electrode erosion in both arcjets and arc heaters (in steady state and at startup). Because electrode erosion (anode or cathode) often determines the lifetime of the device, a thorough understanding of electrode-related phenomena is key to the improvement of lifetime.

Cathode erosion is one of the limiting mechanisms in several classes of electric thrusters. Since cathode erosion depends strongly on the cathode temperature, a quantitative understanding of the effects of cathode operation on the cathode temperature is required. Goodfellow[40] recently developed a cathode model that is a combination of a quasi-two-dimensional thermal model and an improved near-cathode plasma model. Earlier models[41,42] have been improved by adding doubly-charged ions, multiple-gas types, and a submodel of equilibrium ionization/recombination within the ionization region. A number of experimental measurements has been made and a good agreement between model and experimental data has been obtained.[43] Recently, nonintrusive measurements of the cathode temperature and the electron number density at the vicinity of the cathode have been successfully achieved by Cappelli and Storm,[19] using axial emission spectroscopy and the Stark broadening of the wings of the hydrogen Balmer-alpha lines. Zhou[44] has also extensively studied cathode and surrounding plasma conditions in an apparatus designed to produce arcjet-like conditions. The former study found that electron number densities in the near-cathode region are weakly dependent on specific power and that cathode temperatures exceed the melting point of tungsten at specific power levels of 200 MJ/kg and above. The latter study found (among other observations) that, for standard thoriated tungsten cathodes, nonuniform erosion patterns often observed on high current cathodes could be explained by ion bombardment, that both thorium and tungsten evaporate from the cathode and are redeposited outside the cathode spot, and that thorium is depleted with time. Zhou[44] also found that cathode temperature and both electron temperature and number density increase slowly with increasing arc current, but that pressure had little impact on cathode temperature.

Arc attachment at the anode is a troublesome modeling area. If one assumes both chemical and ionization equilibrium (Saha equilibrium), electron density and the electrical conductivity are forced to zero outside of the arc and no physical mechanism exists for current to reach the anode. Collisional coupling between electrons and heavy particles would be capable of sustaining anode attachment in the downstream region. This could be achieved at higher gas densities, such as can be obtained at higher values of flow rate for a fixed power/flow ratio. Calculations under these conditions[45] showed instead a general downstream stretching of the attachment region, to areas of roughly unchanged density, so that electron-heavy particle coupling failed to materialize. The downstream shift was caused by the reduced heat diffusivity at higher densities. Obtaining stronger collisional coupling seems to require either a substantially higher collisional transfer rate than used in these calculations, or perhaps a three-dimensional constriction of the attachment into one or several filaments, in which the plasma density, and hence, the coupling, would be much higher.

The near-electrode region in arc heaters has recently been described for high pressures (100 bar) as consisting of five subzones: 1) the flow-affected zone, 2) an equilibrium ionization-zone, 3) a thick current concentration zone replacing a space-charge sheath used for lower pressures, 4) a work function zone, and 5) a solid-state heat conduction zone.[26] However, emission values obtained from experiments[46] suggest that the near-cathode ionization zone may be partially in nonequilibrium for which a larger (than equilibrium) electron number density would be predicted. The near-electrode model developed for high-pressure application would be worth investigating for application at lower pressures, provided that nonequilibrium ionization was added.[26] A high electron temperature at the electrode surface results from the strong thermal nonequilibrium existing in the annular region connecting the arc at the constrictor exit to the initial part of the nozzle wall.[45] Felderman et al.[26] suggest that near-electrode models should be modified to include nonequilibrium effects to both extend applicability to low pressures and to improve anode model mass-loss predictions.

Arc Instabilities

Harris et al.[47] tested a radially segmented arcjet and observed generally nonsymmetric distribution of current to the segments, with random fluctuations that indicated a multifilament structure of the anode attachment. Similar behavior was also observed by Berns et al.[48] and Pfender[49] through experiments with subsonic arcjet and plasma torches, respectively. While anode and cathode attachments in small arcjets are generally quiescent in nature, instabilities do occur in some cases. In higher-power arcjets, instabilities can lead to very destructive behavior. Observed instabilities may be electrothermal in nature, for example, an overheated region in the thruster may cause higher conductivity in that region, which, in turn, channels more current to further overheat that region and lead to thermal runaway. In cases like this, the relationship between arc phenomena, gas flow pattern, electrode surface physics is not clearly understood and must be explored.

Instabilities similar to those in arcjets have been observed in arc heaters. Large arc fluctuations can cause severe damage to the arc constrictor if the arc approaches the constrictor wall too closely. Direct evidence of arc instability was verified by optical imagery during arc-heater operation.[50] In that study, arc displacements from centerline were recorded as a function of time at three axial locations along the constrictor wall. The typical frequencies were less than 1 kHz for large fluctuations. Accurate modeling of the unstable arc path is required to improve both constrictor design and the orientation of the tangential injection holes in and near the cathode region. An effective model would predict flow stability and the anticipated behavior of the arc-given flow conditions and device geometry. To obtain this predictive capability, better understanding of multicell vortex flow, unsteady vortex dynamics, and other parameters influencing vortex breakdown will be required. In addition, arc stability is also influenced by the coupling of electromagnetic forces and flow turbulence; this coupling requires the inclusion of an additional term describing electromagnetic effects in the turbulence modeling.

Concluding Remarks

This article has been intended to provide the reader with both a brief introduction into the field of arcjet thrusters and arc heaters and a selected overview of research status and directions in this field. Advanced arcjets may play a key role in the deployment and positioning of military spacecraft. These devices share many common design features. Improved arc heaters are required for the cost-effective development of hypersonic aircraft airframe and propulsion technologies. Over the past several years, significant progress has been made in the design and implementation of both intrusive and nonintrusive diagnostic techniques to describe physical phenomena both internally and in the plumes of these devices. Sophisticated modeling efforts have been undertaken with some success. At this point, the development of accurate, efficient design tools (models) is of paramount importance. For this, a much greater understanding of nonequilibrium processes, electrode attachments, arc instabilities, and the interactions between these will be required. Both experimental and modeling efforts are in progress to develop the requisite knowledge in these areas.

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References

[1]Birkan, M. A., and Micci, M. M., "Survey of Electric Propulsion Thruster Applicability to Near Earth Space Missions," *Proceedings of the DGLR/AIAA/JSASS 20th International Electric Propulsion Conference* (Congress Hall, Garmisch-Partenkirchen, Germany) Federal

Ministry of Research and Technology, 1988, pp. 374–379 (ISBN 3-922010-40-7).

[2]Horn, D. D., "AIAA Short Course: Aerothermodynamic Facilities and Measurements, Review of Existing Arc-Heated Facilities," AIAA Continuing Education Dept., Washington, DC, June 1994.

[3]Jahn, R. G., *The Physics of Electric Propulsion*, McGraw–Hill, New York, 1968.

[4]Curran, F. M., and Byers, D. C., "New Developments and Research Findings: NASA Hydrazine Arcjets," AIAA Paper 94-2463, June 1994; also NASA TM 106695.

[5]Butler, G. W., and Cassady, R. J., "Directions for Arcjet Technology Development," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1026–1034; also AIAA Paper 94-2652, June 1994.

[6]Pollard, J. E., Jackson, D. E., Marvin, D. C., Jenkin, A. B., and Janson, S. W., "Electric Propulsion Flight Experience and Technology Readiness," AIAA Paper 93-2221, June 1993.

[7]Curran, F. M., and Callahan, L. W., "The NASA On-Board Propulsion Program," AIAA Paper 95-2379, July 1995; also NASA TM-107036.

[8]Schuster, J. R., LeMay, J. R., Morss, E. P., and Williams, G. E., "Centaur-Derived Propellant Supply System for a Solar Electric Orbit Transfer Vehicle," International Electric Propulsion Conf., Paper 93-204, Sept. 1993.

[9]MacDermott, W. N., Horn, D. D., and Fisher, C. J., "Flow Contamination and Flow Quality in Arc Heaters Used for Hypersonic Testing," AIAA Paper 92-4028, July 1992.

[10]Liepmann, H. W., and Roshko, A., *Elements of Gasdynamics*, Wiley, New York, 1967.

[11]Jorgensen, L. H., and Baum, G. M., "Charts for Equilibrium Flow Properties of Air in Hypervelocity Nozzles," NASA TN D-1333, Sept. 1962.

[12]MacDermott, W. N., Horn, D. D., and Fisher, C. J., "Flow Contamination and Flow Quality in Arc Heaters Used for Hypersonic Testing," AIAA Paper 92-0408, June 1992.

[13]Zana, L. M., "Langmuir Probe Surveys of an Arcjet Exhaust," AIAA Paper 87-1950, July 1987; also NASA TM-89924.

[14]Sankovic, J. M., "Investigation of the Arcjet Plume Near Field Using Electrostatic Probes," *Proceedings of the 1990 JANNAF Conference*, 1990; also NASA TM-103638.

[15]Burton, R. L., and Bufton, S. A., "Exit-Plane Electrostatic Probe Measurements of a Low-Power Arcjet," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1099–1106; also AIAA Paper 94-3299, June 1994.

[16]Burtner, D., Keefer, D. R., and Ruyten, W., "Low-Power Ammonia Arcjet: Numerical Simulations and Laser-Induced Fluorescence Measurements," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1123–1128; also AIAA Paper 94-2656, June 1994.

[17]Pobst, J. A., Spores, R. A., Schilling, J. H., and Erwin, D. A., "Fluctuation of Arcjet Plume Properties," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1107–1113; also AIAA Paper 94-2464, June 1994.

[18]Ling, H., "Near Field Interaction of Microwave Signals with a Bounded Plasma Plume," Final Rept., NASA Grant NCC3-127, Jan. 1991.

[19]Capelli, M. A., and Storm, P. V., "Interior Plasma Diagnostics of Arcjet Thrusters," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1070–1076; also AIAA Paper 94-2654, June 1994.

[20]Zube, D. M., and Myers, R. M., "Thermal Nonequilibrium in a Low-Power Arcjet Nozzle," *Journal of Propulsion and Power*, Vol. 9, No. 4, 1993, pp. 545–552.

[21]Harris, W. J., O'Hair, L. L., Hatfield, L. L., Kristiansen, M., and Grimes, M. D., "Static Pressure Measurements in a 30 kWe Class Arcjet," AIAA Paper 91-2457, June 1991.

[22]Curran, F. M., and Manzella, D. H., "The Effect of Electrode Configuration on Arcjet Performance," NASA TM 102346.

[23]Butler, G. W., Kull, A. E., and King, D. Q., "Single Fluid Simulations of Low Power Hydrogen Arcjets," AIAA Paper 94-2870, June 1994.

[24]Megli, T. W., Krier, H., Burton, R. L., and Mertogul, A., "Two-Temperature Plasma Modeling of Nitrogen/Hydrogen Arcjets," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1062–1069; also AIAA Paper 94-2413, June 1994.

[25]Boyd, I. D., Beattie, D. R., and Cappelli, M. A., "Numerical and Experimental Investigations of Low-Density Supersonic Jets of Hydrogen," *Journal of Fluid Mechanics*, Vol. 280, 1994, pp. 41–67.

[26]Felderman, E. J., MacDermott, W. N., and Fisher, C. J., "Near-Electrode Model for 100-Standard Atmosphere Arc Discharges," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1084–1092; also AIAA Paper 94-2039, June 1994.

[27]Miller, S. A., and Martinez-Sanchez, M., "Multifluid Non-Equilibrium Simulation of Arcjet Thrusters," AIAA Paper 93-2101, July 1993.

[28]Babu, V., and Subramaniam, V. V., "Numerical Solutions to Nozzle Flows with Vibrational Non-Equilibrium," *Journal of Thermophysics and Heat Transfer*, Vol. 9, No. 2, 1995, pp. 227–232.

[29]Flament, C., George, T., Meister, K. A., Tufts, J. L., Rich, J. W., Subramaniam, V. V., Martin, J. P., Piar, B., and Perrin, M. Y., "Non-Equilibrium Vibrational Kinetics of Carbon Monoxide at High Translational Mode Temperatures," *Chemical Physics*, Vol. 163, 1992, pp. 241–262.

[30]Chiroux De Gavelle De Roany, A., Flament, C., Rich, J. W., Subramaniam, V. V., and Warren, W. R., Jr., "Strong Vibrational Non-Equilibrium in Supersonic Nozzle Flows," *AIAA Journal*, Vol. 31, No. 1, 1993, pp. 119–128.

[31]Capitelli, M. (ed.), *Non-Equilibrium Vibrational Kinetics*, Springer–Verlag, Berlin, 1986.

[32]Yardley, J. T., *Introduction to Molecular Energy Transfer*, Academic, New York, 1980.

[33]Dunnwald, H., Siegel, E., Urban, W., Rich, J. W., Homicz, G. F., and Williams, M. J., "Anharmonic Vibration-Vibration Pumping in Nitric Oxide by Resonant IR-Laser Irradiation," *Chemical Physics*, Vol. 94, 1985, pp. 195–213.

[34]Deleon, R. L., and Rich, J. W., "Vibrational Energy Exchange Rates in Carbon Monoxide," *Chemical Physics*, Vol. 107, 1986, pp. 283–292.

[35]Urban, W., Lin, J. X., Subramaniam, V. V., Havenith, M., and Rich, J. W., "Treanor Pumping of CO Initiated by CO Laser Excitation," *Chemical Physics*, Vol. 130, 1989, pp. 389–399.

[36]Babu, V., Aithal, S. M., and Subramaniam, V. V., "Numerical Simulation of a Hydrogen Arcjet," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1114–1122; also AIAA Paper 94-2655, June 1994.

[37]Felderman, E. J., and MacDermott, W. N., "Radiative Heating in High-Pressure Arc Heaters," AIAA Paper 92-2873, July 1992.

[38]Gogel, T. H., Sedghinasab, A., and Keefer, D., "Radiation Transfer Computation in Cylindrical Arc Columns Using a Monte Carlo Method," AIAA Paper 90-2615, July 1990.

[39]Ishi, M., and Kuriki, K., "Optical and Analytical Studies of Arc Column in DC Arcjet," AIAA Paper 87-1086, May 1987.

[40]Goodfellow, K. D., "Theoretical Investigation of Cathode Operation in High-Power Arcjets," AIAA Paper 95-3061, July 1995.

[41]Goodfellow, K. D., and Polk, J. E., "High Current Cathode Thermal Behavior, Part I: Theory," *Proceedings of the 23rd International Electric Propulsion Conference* (Seattle, WA), 1993, pp. 305–318.

[42]Goodfellow, K. D., and Polk, J. E., "Theoretical Operation of Solid Rod Cathodes," AIAA Paper 94-3132, July 1994.

[43]Goodfellow, K. D., and Polk, J. E., "Experimental Verification of a High-Current Cathode Thermal Model," AIAA Paper 95-3062, July 1995.

[44]Zhou, X., "Experimental Investigation of Arc-Cathode Interaction," Ph.D. Dissertation, Cincinnati, OH, Dec. 1995.

[45]Martinez-Sanchez, M., and Miller, S., "Arcjet Modeling: Status and Prospects," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1035–1043; also AIAA Paper 94-2653, June 1994.

[46]Cobine, J. D., *Gaseous Conductor*, Dover, New York, 1958.

[47]Harris, W. J., O'Hair, E. A., Hatfield, L. L., Kristiansen, M., and Mankins, J. S., "Anode Motion in High Power Arcjets," AIAA Paper 92-3838, July 1992.

[48]Berns, D., Sankovic, J., and Sarmiento, C., "Investigation of a Subsonic-Arc-Attachment Thruster Using Segmented Anodes," AIAA Paper 93-1899, July 1993.

[49]Pfender, E., "Electric Arcs and Arc Gas Heaters," *Gaseous Electronics*, edited by M. N. Hirsch and H. J. Oskam, Vol. I, Academic, 1978.

[50]Felderman, E. J., Chapman, R., Jacocks, J. L., Horn, D. D., and Bruce, W. E., III, "High-Pressure Arc Heater Development and Modeling: Status and Requirements," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1044–1052; also AIAA Paper 94-2658, June 1994.