Plasma Aerodynamics: Current Status and Future Directions

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Plasma aerodynamics can trace its origin to the beginning of the space age, and in particular to a time when designers realized that plasmas could have a significant influence on reentry flows. From the 1950s to the 1970s, there was considerable work on magnetohydrodynamic reentry systems and related technology. The recent resurgence in the field was stimulated by the disclosure of the Soviet AJAX vehicle concept in the mid-1990s. This led to an extraordinary international collaboration that has now lasted almost twenty years. Plasma-based flow control seems quite feasible, particularly for local flow control applications where power consumption is low. Plasma-based devices have a low profile, and can provide actuation over short time scales. Plasma-enhanced combustion is a very promising area for both low- and high-speed regimes. Discharges are already being used to break down fuels, enhance ignition, provide flameholding, and promote combustion efficiency. There are a number of potential breakthrough areas in the field that could have strong technological impact on the aerospace industry. Industry seems to be receptive to the adoption of plasma-based technology, but has reservations about technical risk, performance, reliability, and integration. There is a need to identify applications where plasma devices are significantly better than completing technologies, and to demonstrate prototypes in an operational environment. With a century of atmospheric flight and half a century of spaceflight behind us, the aerospace sciences remain a vigorous and exciting field. The new field of plasma aerodynamics contributes to this excitement, and supports diverse aerospace technology needs, from energy efficiency to space access.

Introduction

Although plasma aerodynamics has a history that dates to the beginning of the space age, a surge of activity has occurred in the field since the mid-1990s. There has been strong research interest in plasma-based flow and flight control, plasma-assisted combustion, on-board electrical power generation, and magnetohydrodynamic heat shields. As the field has matured, some of the older concepts are receiving less attention, and emphasis is being placed on different areas like small-scale plasma actuators. The present white paper summarizes the current status of the field, and identifies promising directions for scientific research and technology development.

In 1994, Russian scientists introduced a novel hypersonic flight vehicle concept, AJAX or AYAKS, into the open literature. AJAX was a scramjet-powered vehicle, which incorporated plasma-based technology to enhance combustion and aerodynamic performance. Work had begun on AJAX and its predecessor concept vehicles in the former Soviet Union before 1985, but this work was not made public at the time. In response to AJAX, the US Air Force, through the Air Force Research Laboratory (AFRL) and the European Office of Aerospace Research and Development (EOARD) established the Weakly Ionized Gases (WIG) Program in the former Soviet Republics. The WIG program was created to foster US – Eastern Bloc cooperative research exchange, and has been a strong influence on the recent resurgence of interest in plasma aerodynamics.

Initial research in the United States was directed at understanding the role of plasmas in the performance of the AJAX vehicle. Arguably the most captivating aspect of the plasma effects was the so-called "plasma magic," the weakening of hypersonic shock waves by plasmas. The Air Force Arnold Engineering and Development Center (AEDC) performed ballistic projectile experiments to attempt to reproduce early (ca. 1978) Russian experiments. Their results generally confirmed the Russian observations. Subsequently, the Air Force Office of Scientific Research (AFOSR) assembled a team to conduct modeling and experiments. Plasma magic was eventually explained as a plasma-based heating effect, albeit a result of complex and subtle physics. Research on aerospace plasma technology has now expanded far beyond these initial efforts, and includes a broad international collaboration.

Weakly ionized plasmas offer significant potential benefits for flight vehicles. The plasma technologies of interest fall into two main categories: plasma actuators for aerodynamic control, and plasma assisted combustion for propulsion.

As flush-mounted electronic devices with no moving parts, plasma actuators offer the possibility of very fast response times and low profile. Use of these actuators has been explored for re-attachment of separated flow, supersonic and transonic shock mitigation, control of shock-shock and shock-boundary layer interactions, delay of laminar-to-turbulent transition, and other effects that reduce drag, enhance lift, and eliminate undesirable transient phenomena in off-design conditions. In reentry flight, where plasma is generated through aerodynamic heating, the plasma layer can be manipulated with onboard magnets for electrical power generation, flight control, and heat transfer mitigation.

Plasma-assisted combustion technologies can shorten ignition time, enhance fuel-air mixing, increase flame speed, provide stable flameholding, and enable reliable operation with lean mixtures. The application of plasma torches to scramjets allows the possibility of ignition over a wide range of conditions. Near-term applications will lie with localized discharges, because of low energy requirements and ease of integration within a harsh environment. Short-pulse discharges (nanosecond and below) are well suited to high-speed environments because they have the ability to couple energy into the flow on short time scales. Laser ignition, in which a tightly-focused beam generates localized plasma, is a promising alternative approach.

Research in academia, industry, and government has produced interesting and promising results. The mechanisms of plasma effects on aerodynamics and propulsion are now fairly well understood, but the Technology Readiness Level (TRL) is still relatively low. For the most mature technologies, component or prototype validation has been carried out in a relevant environment (TRL 5-6), but many concepts have not yet been brought to that stage maturity. For plasma technology transition to application on flight vehicles, a number of additional issues have to be addressed. The critical issues include relative control authority of plasma devices, electrical power requirements, overall weight of the plasma systems, technology integration issues, and environmental factors. Near-term application of plasma technology will come in the form of modifications to improve the performance of existing platforms. Nonetheless, the greatest benefits of plasma technology will come when it is incorporated at the conceptual design stage, with the design paradigm focused on this new approach.

Plasma-Based Flow Control

Over the past several decades, a number of control techniques have been developed to create or maintain a desired flow pattern. Flow control techniques are chosen based on several factors, including the flow configuration, Mach number, and Reynolds number. Successful endeavors always require an understanding of both the flow physics and the actuation technique.

A flow control device may be passive or active. Passive control almost always involves geometrical modifications, such as vortex generators on a wing or chevrons on an exhaust nozzle. Passive control devices are always in operation, regardless of need or performance penalty. Active flow control, on the other hand, involves the regulated addition of energy or momentum to the flow. Active control can be turned on or off as needed, but it involves significant effort and cost.

Actuators are at the heart of active flow control implementation, and have been the weakest link in the development of flow control technology. Plasma actuators are able to address some of this deficiency; they offer the possibility of low weight, low profile, no moving parts, energy efficiency, durability, ease of use, scalability, high amplitude, wide bandwidth, and rapid response.

Research and development on plasma actuators has included direct current, alternating current, radio frequency, microwave, arc, corona, and spark discharge actuators. The two primary mechanisms of plasma-based flow control include generation of a body force (electrohydrodynamic and magnetohydrodynamic interactions) and thermal effects (Joule heating and relaxation of internal energy states). The field is still evolving, and a variety of actuator concepts are currently being explored. Flow control using four of the more-studied actuators will be briefly discussed here.

Alternating current, dielectric barrier discharge (AC-DBD) plasma actuators impose a force on the flow through electrohydrodynamic interaction, and have been used primarily to control flow separation. Their application was initially limited to low-speed flows, but has recently been extended to a somewhat higher speed regime. In recent years, these AC-DBDs have been applied to boundary layer transition control, with successful in-flight demonstration. Continued improvement of these actuators is anticipated with new electrode configurations, optimized dielectrics, and optimized high voltage driving waveforms.

Nanosecond-pulse, dielectric barrier discharge (ns-DBD) plasma actuators are similar in configuration to AC-DBD actuators, but their input waveform is a short pulse instead of a sinusoidal waveform. Their flow control effect is primarily a result of heating; the body force generated by current ns-DBD designs is only a small fraction of that of an AC-DBD. The rapid heating of the air near the actuator generates compression waves and introduces streamwise vorticity. In flow over an airfoil, these perturbations can trip a laminar boundary layer to turbulence, which can mitigate separation. Further, an ns-DBD actuator can attach separated flows under stall conditions by exciting the instabilities in the separated shear layer. This concept shows promise for improving aircraft performance in takeoff and approach.

Localized arc filament plasma actuators (LAFPAs) also operate through gas heating, and have a flow effect similar to that obtained with ns-DBDs. They use a spark discharge across pin electrodes to generate high amplitude, short-duration perturbations to the flow. An alternative configuration introduces transverse plasma filaments into the flow, with a repetition frequency tuned to flow instabilities. They have been successfully used in a wide variety of flows with inherent instabilities, including subsonic and supersonic cold or hot jets, shock / boundary-layer interaction, and cavity flows.

The spark jet, or pulsed plasma jet, is a hybrid actuator. It employs a spark discharge across electrodes housed in a small cavity. When the actuator fires, the rapid heating generates a synthetic jet out of the cavity, which injects high-momentum fluid into the flow. These actuators can introduce a strong perturbation into the flow, and have been successfully applied to shock-wave / boundary-layer interaction control.

While plasma actuators have been demonstrated to be very effective in laboratory environments, they are subject to reliability and scalability concerns that have inhibited their widespread adoption for flight applications. Some of the chief concerns include electromagnetic interference, weather effects, durability, and maintenance. For many actuator designs, performance deteriorates over time through electrode erosion and plasma-initiated chemical degradation of the dielectrics, which must remain relatively pristine to avoid high voltage arcs and failure. Steady progress is being made, but additional emphasis needs to be placed on addressing such concerns.

Future efforts in plasma-based flow control must balance emphasis on specific applications and fundamental physics. In the former, the focus must be on reliability, scaling, efficiency, and miniaturization. This will require collaboration among experts in fluid dynamics, plasma physics, power supply engineering, and materials science. More fundamental research will serve to provide a more thorough understanding of the actuators and their influence on the flow field, leading to better designs, targeting specific applications. Study of applications and fundamentals must be closely linked for long-term success.

Plasma-Enhanced Combustion

Today, 85% of primary energy conversion processes are based on combustion, and this fraction is expected to remain stable in the foreseeable future. Because of the increasing financial cost and environmental impact of fossil fuels, however, industry faces ever more stringent challenges to improve combustion efficiency, reduce pollutant emissions, control combustion instabilities, and develop novel propulsion systems. Plasmas have long been used in combustion, beginning 150 years ago with the spark ignition system invented by Belgian engineer Etienne Lenoir. But the AJAX project (see Section 1) triggered interest in the use of plasma discharges as a means to provide in-place, on-demand enhancement of fuel-air reactivity, and thus launched the new field of plasma-assisted combustion.

Over the past two decades, the worldwide plasma-assisted combustion research community has been able to achieve great progress in the understanding of the fundamental physico-chemical effects of various types of plasma discharges in combustion, and has carried out successful demonstrations with laboratory-scale devices. Today, plasma-assisted combustion is seen as one of the most promising combustion strategies, and a key field for novel applications of high-pressure plasma discharges.

Since the mid-1990s, several successful proof-of-concept experiments have been conducted in small- to large-scale laboratory devices, and clear beneficial effects of plasma-assisted combustion have been demonstrated. For example, reduced ignition delays and enhanced flame stabilization in supersonic flows have been achieved by applying direct-current (DC), microwave (MW), or nanosecond repetitively pulsed (NRP) discharges to both flat plates and cavity-based flame holders. “Rail gun” plasma spark plugs, based on a self-induced magnetic field, have been shown to improve ignition and reduce electrode wear, and are currently being marketed for automotive, turbine, and pulse detonation engine applications. Ignition delay times have been reduced by several orders of magnitude with nanosecond discharges, allowing, for example, the operation of Pulse Detonation Engines (PDE) at higher frequencies, and thus increased thrust and higher performance.

Flame stabilization, particularly in lean premixed regimes where lower burnt-gas temperatures lead to reduced formation of nitrogen oxide compounds (NOx), has been achieved with NRP discharges for a wide variety of fuels (from natural gas and propane to kerosene) at pressures up to several bars. The ability of plasma discharges to enhance the ignition of ultra-lean fuel-air mixtures, or mixtures with increased exhaust gas recirculation (EGR) fractions, has also been demonstrated. This has the potential to increase the efficiency of gasoline engines and to reduce NOx emissions in diesel engines.

Active plasma control of thermoacoustic combustion instabilities in the range of hundreds of hertz is being investigated as a method to reduce NOx emissions, reduce the propensity for flashback and blowoff, increase heat transfer, mitigate structural fatigue or damage, simplify combustor design, and expand operability. Compared with mechanical or acoustic control devices, plasma discharges offer the advantages of relatively easy practical implementation (they can often be created across conventional spark plug electrodes), and fast temporal response and high actuation bandwidth. In most of these applications, the beneficial effects have been obtained with low power discharge consumption, typically with less than 1% of the power released by the flame.

Study of liquid and liquid-vapor interface plasmas has intensified considerably over the last few years. Some of the features of these plasmas may also have a significant potential for aerospace applications. One example is rapid pressure rise during pulsed breakdown in a liquid fuel, which may generate transient supercritical conditions and have a strong effect on the dynamics of fuel injection, atomization, and mixing with the flow.

These many opportunities for improvement of combustion processes present a compelling picture. The nearest term applications are most likely in ignition, with some concepts already being tested in realistic environments. These applications have the potential to improve ignition reliability, achieve more complete combustion, and minimize electrode erosion. Cold startup performance may also be improved. With enhanced reliability, the use of leaner fuel-air mixtures becomes practical, and operation with repeated pulses may enable combustion to proceed at extinction levels below those previously achievable.

Applications in high-pressure environments associated with internal combustion diesel and gasoline engines, natural gas and liquid hydrocarbon fueled turbines, and electrical power generators will be especially important, given the ubiquity of that equipment for mobile and stationary power. Even a small improvement in performance or reliability will be a great achievement, and the reduction of emissions will have a wide impact. Implementation in atmospheric pressure environments, such as natural gas and oil fired home heating and hot water heating units, may lead to reduction of pollution and improved efficiency through leaner, lower-temperature combustion.

An important long-range payoff may be the augmentation and control of high-speed ramjet and scramjet engines and of jet afterburners. Relevant plasma-based technologies show promise for volumetric ignition, flame holding, increased mixing, flame speed enhancement, and acoustic control. For many applications, existing combustor designs may be utilized and the plasma effects introduced through advanced spark plug technology or injector and fuel delivery modifications.

Supporting Science

In order to make continued progress in plasma aerodynamics, certain supporting scientific areas require development. In particular, there is a need to improve the simulation and measurement of aerospace plasmas.

There are two main challenges for numerical simulation of aerospace plasmas. The first is the disparity in the time and length scales for an electrical discharge in a large-scale gas flow. Important physics occurs on the scale of molecules, the actuator, the air vehicle, and the flight path. Thus, the time scales involved range from sub-nanosecond molecular processes to several hours of flight time. Spatial scales range from nanometer molecular scales to megameter global flight paths. Significant progress has been made in multiscale computations through the use of unstructured meshes with a dynamic range in spatial resolution of 104, time-slicing techniques which enable a dynamic range in timescales of 109, and kinetic-fluid hybrid models that enable accurate representation of non-equilibrium processes. These techniques need to be refined to address the conditions of interest. These multiscale challenges have also motivated the use of reduced-order models, but there is a need to corroborate their accuracy with experiment and high-fidelity computations.

The accuracy of numerical modeling also depends strongly on the chemical kinetic model. The kinetics of plasmas in air and air-fuel mixtures is extremely complex, and care must be taken in calculations to stay within the bounds of validity of a plasma kinetic model. There is a lack of detailed experimental data to compare with new kinetic mechanisms. In general, there is a compelling need for consistent effort to establish the accuracy of plasma aerodynamic modeling.

Kinetic processes in nonequilibrium air and fuel-air plasmas remain far from understood, in spite of considerable experimental and kinetic modeling advances achieved over the last two decades. For example, the importance of rapid thermalization of internal energy on a sub-acoustic time scale, which generates high-amplitude, high bandwidth pressure perturbations, has been recognized only recently. Several aerospace technology areas that would benefit from detailed insight into plasma energy transfer processes and chemical kinetics include high-speed flow control, fuel injection and reforming, and combustion.

Quantitative insight into coupling between low-temperature plasma kinetics and combustion chemistry also remains a challenge. Conventional combustion chemistry mechanisms have been developed and validated for relatively high temperature conditions. Applicability of such mechanisms at temperatures below ignition temperature, common in plasma-assisted combustion environments, is uncertain at best. It must still be determined whether they can be used as a basis for a predictive plasma-assisted combustion chemistry mechanism. Quantitative insight into kinetics of nonequilibrium plasma assisted flow control, fuel oxidation, ignition, combustion, flameholding, and fuel reforming will not be feasible without detailed kinetic modeling. Truly predictive analysis of air plasma and fuel-air plasma kinetics, even in relatively simple geometries, remains a formidable challenge.

Multi-fluid models, including separate modeling of the motion of electrons, ions, and species with different internal energy states, are also under study. The fundamental physics may also include kinetic effects, which can lead to phase space dynamics that manifest in large-scale effects of the flow dynamics. Additional work on rigorously formulating the governing equations and boundary conditions is still needed.

The inherent complexity of plasma-aerodynamic flows poses unique measurement challenges. In particular, prediction from first principles requires detailed knowledge of the partitioning of plasma energy between translational, rotational, vibrational, and chemical internal energy modes of flow constituents, as well as the ability to predict the coupling of this non-equilibrium fluid state to the gas dynamics of the flow field. The last twenty years have seen enormous growth in new aerodynamic measurement technologies, however, and the community is now poised to make significant advances. Carefully constructed, coupled experimental and computational campaigns, where high-fidelity computer simulations are validated by the available experimental measurements, could also significantly advance our understanding.

Three particularly important challenges should be noted. First, there is a need to develop new approaches for non-intrusive measurement in the aerodynamic environment of fundamental plasma properties, in particular the electric field, electron density, and electron temperature. Second, there is need for new technologies and methodologies that can provide data with space and time resolution at scales of interest for unsteady turbulent flows. Finally, there is the need to develop the capability to capture quantitative data in three dimensions. The last decade has seen extremely rapid advances in laser and optical technology, which researchers are exploiting to provide revolutionary new capability for aerodynamic measurement.

Potential Breakthrough Areas

Breakthroughs in aerodynamic plasma technology will come from the improvement of devices that are currently under study, from the implementation of new concepts, and from the development of new experimental facilities and materials. Significant advances in plasma-assisted combustion, plasma-enhanced aerodynamics, and measurement technologies are anticipated.

Plasma-based methods are currently under development for flame speed enhancement, volumetric ignition, reduction of nitric oxide formation, mixing enhancement, stabilization of combustion at reduced equivalence ratio, control of acoustic modes, and low temperature combustion. Breakthroughs in these areas are to be expected as better modeling provides better understanding of the most effective mechanisms for interaction, and as more effective actuator configurations and energy deposition mechanisms are developed. Such developments may include sub-nanosecond high voltage pulse capabilities for the creation of discharges suitable for operational combustors, and efficient, open-cavity, high-power pulsed microwave systems for the control of flame propagation speeds in turbulent combustion environments. Laser and nanosecond-pulse guided microwave energy deposition may provide methods for more direct control of ignition location and temperature, and high voltage, nanosecond-pulse ignition methods may lead to greater combustion stability, volumetric ignition, reduced nitric oxide emission, and low equivalence ratio operation.

For aerodynamic processes, plasmas can be created on or off the surface. Surface discharges are being studied for the control of boundary layer separation, control of laminar to turbulent transition, drag reduction, and suppression of local heating. Off-body and volumetric plasmas are being studied for drag reduction, reduction of heat transfer rates, vehicle steering, power extraction, and reduction of sonic boom.

New methods for magnetohydrodynamic (MHD) control and power extraction are already leading to innovative designs for hypersonic vehicles. Flight control and reduced surface heating can be achieved through the use of a magnetic field interacting with the bow shock, and the concept is currently being implemented for flight tests. Power extraction during reentry may also be possible through the use of MHD interactions with internal or external flows. Internal flows benefit from shock interactions for ionization, and for these flows the technology is potentially applicable at lower Mach numbers.

Increased effectiveness of surface plasma actuators is anticipated with new electrode configurations, optimized dielectrics, and optimized high voltage driving waveforms. Breakthroughs are expected to occur with multi-electrode configurations for thrust generation and shock wave focusing. Further breakthroughs may arise from new surface materials that allow changes in the fundamental structure or the temporal evolution of the discharge. Additional surface-based concepts can make use of plasma arrays that are capable of generating shock waves that propagate away from the surface and coalesce to generate vorticity or drive acoustic waves for control of near-surface flows. Plasma-generated far-ultraviolet radiation may also be of use for rapid near-surface energy addition through direct absorption and molecular dissociation of oxygen.

Laser plasma ignition is of growing interest in a number of applications including reciprocating engines (mobile or stationary), ground based turbines, aero-turbines, rocket engines, and scramjet engines. Existing laser-ignition approaches are already showing benefit for extending the lean limit and improving reliability in aero-turbines. New approaches using multiple laser pulses to tailor the plasma are being investigated. Examples of approaches that could lead to breakthroughs include use of an overlapped nanosecond pulse to sustain the plasma filament generated from a femtosecond laser, and use of an initial pre-ionization pulse followed by energy addition and heating by a second pulse. Such approaches, which decouple the initial ionization from the subsequent energy addition (avalanche), may allow increased volume of the ignition kernel, formation of partially ionized plasmas with controlled temperature (for thermal ignition), or plasmas with longer lifetime, and/or reduced pulse energy requirements (allowing use of smaller, less powerful sources). These new means of laser plasma formation may also benefit other applications, including waveguides for microwave transmission, stand-off detection of hazardous agents, and lightning protection.

Breakthrough technologies in the measurement area will be enabled by the development of new devices that are capable of interactiwith air and combustion environments in ways that are not feasible or practical today. Perhaps the most promising of these is the rapid progress toward the development of efficient, very short-pulsed, precision controllable, high-power, high repetition rate lasers. These lasers will open up new methods for real time data acquisition as well as off-body energy addition, efficient volume ionization methods for MHD applications, and volumetric, selective radical production for combustion reaction and ignition control. With more compact, higher efficiency lasers, operation in flight will be a practical reality.

Summary and Conclusions

Plasma aerodynamics can trace its origin to the beginning of the space age, and in particular to a time when designers realized that plasmas could have a significant influence on reentry flows. From the 1950s to the 1970s, there was considerable work on magneto-hydrodynamic reentry systems and related technology. The recent resurgence in the field was stimulated by the disclosure of the Soviet AJAX vehicle concept in the mid-1990s. This led to an extraordinary international collaboration that has now lasted almost twenty years.

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