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RADIO FREQUENCY (RF) HEATED SUPERSONIC FLOW LABORATORY

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Abstract

A unique supersonic flow apparatus which employs an inductively-coupled, radio frequency (RF) torch to supply high enthalpy source gas to the nozzle inlet is described. The main features of this system are the plasma tube, a cooled nozzle assembly, and a combustion/expansion chamber with a heat exchanger. A description of these components with current test data is presented. In addition, a discussion of anticipated experiments utilizing this system is included.

Introduction

The resurgence of interest in hypersonic flight, as exemplified by the National Aerospace Plane (NASP) and proposed aeroassisted planetary missions (which take advantage of aerobraking maneuvers in the planetary atmosphere as a means of attaining orbit), place heavy emphasis on the predictive capability of computational based techniques. Of particular importance for such flight scenarios is the interplay between chemical reactions and fluid dynamics. For example, modeling of the H_2-O_2 combustion process, envisioned for the NASP vehicle's SCRAMJET engine, can employ chemistry models composed of 18 different reactions¹. The effects of chemistry on supersonic flowfields can manifest themselves in other ways. Menon, Anderson, and Pai², noted in their study of a single chemically reacting supersonic mixing layer (an appropriate physical system for a SCRAMJET in terms of its chemical complexity), that the inherent chemical reactions produced a decrease in flow stability. Certainly in a general sense, chemical reaction will influence turbulence and mixing (and vice versa) in such high speed flows. The question to resolve is what is the actual degree of this interdependence.

With aerobraking maneuvers, spacecraft trajectories will be largely confined to the low density regimes of planetary upper atmospheres. Predicting flowfield properties is difficult in this region because of non-equilibrium effects, i.e., the gas in the shock layer is not in chemical or thermodynamic equilibrium. Thus, non-equilibrium radiative heating may be the dominate heating

mechanism³ and the reaction chemistry may be difficult to assess.

Successful design of efficient supersonic combustion systems as well as drag-inducing structures for aerobraking missions depends to a considerable extent upon computational chemistry and fluid dynamic (CFD) modeling. Validation of such code predictions by appropriate experimental measurements is critical. The ability to qualitatively and unambiguously examine the coupling of chemical reactions with gas/fluid dynamic processes in various supersonic and/or hypersonic flows is, however, somewhat limited with current experimental facilities due predominantly to flow contamination. For example, vitiated-air driven flows suffer from water contamination while flows in arc-heated wind tunnels contain electrode contaminants. Other test facilities such as shock tunnels, although relatively free from chemical contamination, have the major disadvantage of short (millisecond) run times. Resistive heater-driven systems offer clean, continuous flows but their operating stagnation temperatures (~2000 K) limit the ultimate attainable flow speeds. The RF-driven supersonic flow system, currently under development at Los Alamos National Laboratory, effectively minimizes the aforementioned test facility difficulties with studying fundamental flow processes influenced by chemistry.

Description of the Experimental Supersonic Flow System

The RF plasma torch-driven supersonic flow system is being constructed to provide a high Mach number, contamination-free flow field for experimental studies. It must be noted that this system, as it is currently being assembled, represents a laboratory device only and should not be viewed as a large scale test facility. The ability to scale an RF plasma system, however, for higher flow rates and operating pressures is certainly feasible.

The unique feature of this flow system is the inductively-coupled plasma torch used to generate high enthalpy source gases for expansion through supersonic (and hypersonic) nozzles. Such a device was chosen as the system driver because the absence of electrodes minimizes interfering chemical contamination in the flow (i.e., the plasma is maintained without contacting electrodes). The use of radio frequency heating as a means of producing a clean, high temperature gas for ground aerodynamic test facilities has been suggested by Rhodes and Keefer⁴.

As shown in Fig. 1, the primary components of this system are the aforementioned plasma torch, cooled supersonic nozzle, and expansion chamber with heat exchanger. These assembled components are tied into a gas feed system and are evacuated by a high capacity vacuum system. A detailed description of the system components is included below.

The Inductively Coupled Plasma Tube

Theory of Operation

In general terms, the radio frequency plasma tube works in the following manner. Gas is flowed through a nonconducting, typically cylindrical chamber, which is surrounded by several turns of a coil directly coupled to a radio frequency generator. With the coil active, the gas is subject to an alternating magnetic field component directed along the cylinder's axial length. This magnetic field component induces circumferential currents in the gas. The strength and radial depth of these "eddy" currents depends upon the conductivity of the gas as well as the operating frequency of the RF generator. The resulting conductivity (which is a function of the ionization fraction of the gas) determines the degree of ohmic (I^2R) heating achieved in the gas. This ohmic heating is balanced by heating losses through the typical heat transfer mechanisms, namely, conduction, convection and radiation. Radiative losses are generally the most severe, and efficient plasma tube operation requires plasma temperatures which maintain sufficient ionization yet minimize radiative losses.

Los Alamos ICP Tube Configuration

A photograph of the plasma tube used in the Los Alamos experimental facility is shown in Fig. 2. This tube is of in-house design (Hull⁵) and quite novel in its construction. It represents an attempt to combine the features of the unshielded and shielded plasma tubes thereby producing a superior tube. Prior to discussing this hybrid tube's characteristics it is useful to review the general features of both the shielded and unshielded plasma tubes.

The unshielded tube represents the simplest form of plasma tube. It consists of a load coil wrapped around a dielectric material which is typically quartz. The plasma diameter in the unshielded tube increases with increasing gas pressure or input power. The presence of the dielectric between the load coil and the plasma introduces capacitive (electric) coupling to the plasma. It is thought that this capacitive coupling may account for the growth of the plasma diameter as the induction coil voltage is increased⁶. Such a behavior is detrimental to extended operation because the high temperatures associated with plasma expansion will eventually cause the quartz tube to fail. Many schemes have been devised to confine the expanding plasma while simultaneously cooling the quartz enclosure, however, none have proved entirely successful over the desired range of operating conditions.

By contrast, the shielded plasma tube has no line-of-sight path between the induction coil and the plasma. As a result, the ionizing potential in the tube is lowered because of a reduced electric field strength and with increasing load coil power, the plasma diameter shrinks. This electromagnetic pinch will eventually cause the plasma

to disappear. The desired plasma tube would be one in which the electric field strength and resulting gas ionization would increase as load coil power is increased, thereby balancing the also increasing electromagnetic force.

The Los Alamos plasma tube incorporates features of both a shielded and unshielded tube. The plasma is contained within a region surrounded by a shield comprised of overlapping segments. Enclosing this segmented shield is a quartz cylinder sealed O-ring sealed to allow tube volume evacuation and operation at sub-atmospheric pressures. The load coil is positioned around this cylinder. Early versions of this tube contained a shield with large gaps between its segments. During operation, these tubes exhibited electrical breakdown in the air gap between the load coil and the quartz. This breakdown was due to ionization of the air by intense plasma-emitted UV radiation. The overlapping shield segments solved this problem by eliminating the direct line-of-sight path between the plasma and the coil elements. The Los Alamos tube exhibits the desired characteristics of both the shielded and unshielded plasma tube (i.e., the plasma discharge is maintained without shrinkage as the load coil power is increased. The tube achieves these operating characteristics largely through modifications to the interior surfaces of the shield segments. The exact nature of these modifications cannot be disclosed at this time as the concept is undergoing patent review. The modifications, however, extend through the active plasma region and act to increase the number density of conducting species in the vicinity of the segments. The electromagnetic fields sweep these species into the plasma thus maintaining the discharge as coil power is increased.

The Los Alamos tube is approximately 40 cm in length with the shield segments comprising 20 cm of this total length. The twelve copper segments are cooled by high pressure (150 psi) water entering (and exiting) the six fittings situated in the cylindrical brass cylinder above the segments. The inside diameter of the segmented ring is approximately 5 cm. The quartz shield can also be seen surrounding the shield segments. The coil from the RF generator is positioned around the quartz cylinder. Observation of the plasma is possible through a quartz window situated on the top of the tube assembly. Six 1" diameter rods provide structural strength and stability to the entire tube and allow for horizontal mounting without stressing the quartz enclosure. The bottom-located, water-cooled, copper plate is fastened to the transition assembly which carries the hot gas to the nozzle inlet.

The Radio Frequency (RF) Generator

For initial experiments, RF power is supplied by a 50 kW unit (LEPEL Corporation, model T50). The generator is comprised of a high voltage DC power supply and an oscillator section. The oscillator section consists of a

tank circuit (essentially a capacitance-inductance circuit), amplifier, and feedback circuit. A modified Hartley oscillator is employed in the LEPEL generator. With such a design, the feedback coil (which is variable for this generator) is included as part of the tank coil and is connected to the grid portion of the amplifying triode tube. The feedback voltage can be adjusted by varying not only the grid coil but also the tap location to the tank coil. Changing the feedback voltage provides flexibility for matching a wide variety of loads. The load coil which feeds the plasma tube is connected to the tank circuit via a shielded, water-cooled coaxial line. Ultimate control of RF power applied to the plasma torch is provided by varying the DC voltage level applied to the oscillator tube. The operating frequency of the generator is determined by the tank circuit. For the 50 kW unit, the output frequency can be varied between 150 to 450 kHz. The ability to change output frequency also allows flexibility in load matching.

Radio frequency generator power is an important consideration for high pressure torch operation. Figure 3 (ref. 6) provides data on minimum torch sustaining power as a function of generator frequency for argon, air and hydrogen. Note that for an operating frequency of 450 kHz, power requirements increase by approximately a factor of 10 (8 to 80 kW) as one increases argon torch pressure from one to five atmospheres. Power requirements for plasma torches employing molecular species are even more severe (dissociative processes absorb substantial energy prior to ionization events). For this reason, Los Alamos will upgrade the 50 kW generator to a similarly-designed 200 kW unit subsequent to completion of low power experiments.

The Supersonic Nozzle Assembly

As noted previously, the plasma tube is coupled to the nozzle assembly via O-ring sealed copper flanges. The hot gas exiting the plasma tube first traverses a water-cooled channel internal to the transition apparatus (approximately 15 cm in length, 5 cm in width) before encountering the nozzle entrance area. The nozzle, pictured in Fig. 4, is physically situated inside the expansion chamber. The nozzle is simplistic in design employing straight converging (subsonic section) and diverging walls (in the supersonic section) to achieve a Mach 2 flow at the exit ($A_e/A^* = 1.5$) when used with argon. A slight radius is used at the throat point. With a throat area of 0.703 cm^2 , and a projected operating source (inlet) temperature of 5000 K, a flow rate of 10.2 gm/s should be established when a pressure of two atmospheres is applied at the nozzle inlet (again using argon as a test gas).

The exploded view of the nozzle shows the water passages employed to provide cooling for the nozzle sections. A separate recirculating cooling loop with a heat exchanger has been designed and assembled to cool the nozzle and associated transition hardware. This system can supply

10 gpm at 150 psi to the entire nozzle assembly and remove approximately 30,000 BTU/hr. Heat transfer calculations made with a finite element code predict that with such a cooling system, nozzle wall temperatures will not exceed a steady state value of 165 °C (438 K), well below the softening temperature for the copper. Thus, even for the throat area where heating is expected to be the most severe, sufficient cooling is achieved.

Planned experimental studies on supersonic combustion processes require a nozzle that will expand a simulated air mixture of argon and oxygen to supersonic velocities for interaction with slower moving fuel streams. For such a nozzle design, one must take into account the change of state of the gas (e.g., specific heat ratio) as it reaches higher temperatures. For the argon (only) flowing nozzle employed in the initial set of experiments, there is practically no change of state for the gas up to temperatures of 5000 K. Nozzle design calculations are therefore more straightforward.

The Expansion Chamber and Heat Exchanger

The gas exiting the nozzle does so into a rectangular, box-shaped chamber whose pressure can be regulated. This chamber, shown in Fig. 5, is constructed of aluminum and cooled by interconnected sets of copper tubing attached to the chamber's surface by high conductivity, high temperature cement. The chamber contains sixteen window ports with a set of four on each side of the chamber. The eight windows closest to the nozzle assembly are of a racetrack configuration and allow good optical access to the flowfield present downstream of the nozzle exit. The remaining eight windows are circular in shape. High quality fused silica is utilized for all window material to ensure wide-range, optical transmission characteristics. This chamber was designed to allow probing of reactive flows using non-intrusive, laser-based diagnostics. Applicable diagnostics are being developed in parallel with the experimental supersonic flow facility.

The heat exchanger housing is coupled directly to the downstream flange of the expansion chamber (also seen in Fig. 5). This heat exchanger works off of house cooling water and can safely remove 150 kW in continuous operation. Immediately downstream of the primary heat exchanger is a manual throttle valve used to establish background pressures in the expansion/combustion chamber. Attachment to the primary system vacuum line is done after the throttle valve. A photograph which shows the plasma tube coupled to the expansion/combustion chamber is presented in Fig. 6.

Non-intrusive diagnostics represent the least interfering means of characterizing supersonic reactive flows. Such diagnostics, however, require the use of windows to access the reactive region. In general, these windows are made part of a combustion flow facility test section. They require a gas sheath or film cooling to

protect them from generated high temperatures as well as reaction with adverse combustion-produced species. The use of an expansion chamber in the Los Alamos system for combustion studies allows the optical windows to be removed from direct contact with the reactive zone. This feature has the advantage of not requiring any film cooling mechanism. In addition, the expansion chamber exit pressure values are easily controlled and new experimental apparatus can be readily incorporated in the flow system.

Gas Feed and Vacuum System

Introduction of gas to the torch is accomplished through a dual stage, dome loaded regulator-based system with final control provided by a low range (0-50 psia) regulator. The source of gas (currently, argon, helium, nitrogen, and oxygen) for the system is high pressure, tube trailers. Gas flow rates are monitored by a bank of parallel-connected flow meters. A variety of relief valves positioned at various locations in the gas feed system protect from inadvertent, excessive pressurization.

The vacuum system for the RF supersonic flow system is comprised of two Kinney KMBD 2700 systems operating in parallel. Each system is a combination of two positive displacement pumps; a high vacuum mechanical booster pump and an oil sealed, rotary piston backing pump. This combination provides a pumping rate of 5000 CFM at pressures between 0.1 and 30 torr and 1700 CFM at pressures between 30 and 760 torr. Pneumatic gate valves isolate the pumps from the primary system vacuum line. The entire vacuum system is controlled from a remote panel positioned adjacent to the gas feed/control system. In addition to the continuous pumping capacity offered by this system, the primary vacuum line is also connected, by way of an additional pneumatic valve, to a ~800 ft³ blowdown tank. Such a tank provides an almost unlimited, albeit short duration, pumping capacity if desired.

Initial Test Results

The Plasma Tube

To date, the test results on the tube are very encouraging. The tube will initiate plasma production at relatively high pressures with no special starting apparatus. There is no evidence of excessive electromagnetic pinch or plasma instability up to the power limit of the generator. The radial distance between the plasma and the segmented shield is sufficient. The observed efficiency for this tube is at least twice that of existing shielded plasma tubes. For example, with the plasma on (argon gas) and a static tube pressure of one atmosphere, the measured power to the oscillator tube is 64.5 kW (generator plate voltage = 8.6 kV, generator plate current = 7.5 amps). With the plasma off and the same tube conditions duplicated, the power to the oscillator tube is 29.2 kW. Therefore, the power to the plasma is 35.3 kW (64.5 kW -

29.2 kW) and the calculated efficiency is then 55%, a very good value. Additional tests have been performed with one atmosphere mixtures containing 75% nitrogen and 25% argon. No problems were noted and efficiencies remained high.

The Mach 2 Nozzle

To establish a performance baseline for the high temperature supersonic nozzle, room temperature argon gas was exhausted through it and a pitot tube (0.016" OD) employed to characterize the resulting flowfield. This pitot tube is connected to a traverse system which allows vertical scans along the short axis of the nozzle. Movement of the entire assembly to various positions downstream of the nozzle exit is also possible. From the measured impact pressures a centerline exit Mach number of 1.97 ± 0.01 was calculated. This Mach number is arrived at through several measurements taken with nozzle stagnation pressures of one and two atmospheres. Using both Schlieren images and pitot tube pressure traces, the best matched exit pressures conditions were determined to be 110 and 220 torr for stagnation pressures of 760 and 1520 torr, respectively.

Future Testing, Experiments, and Diagnostics

The flow system will be operated with argon initially. System variables such as gas pressure and flow rates as well as tube operating frequency and shield voltage need to be examined to maximize efficiency and define system performance levels. Emission measurements will be used to estimate plasma tube and nozzle source operating temperatures. The nozzle generated flowfield will be characterized using water-cooled pitot tubes. The next activity will be to change the gas mixture to argon plus oxygen (of various percentages) to ultimately simulate an air-like gas. Depending upon results, real air may then be fed into the plasma tube.

The next phase of the laboratory experimental plan will involve an investigation of the properties of a reacting supersonic shear layer. This shear layer will be generated by pulse injecting cold, hydrogen gas into a high temperature, high speed air-like stream. The supersonic nozzle for expanding the high temperature mixture will have a two dimensional, rectangular configuration. Calculations performed with the AeroTherm Chemical Equilibrium (ACE) code, which takes into account changes in state of a gas as a function of temperature, predict that for a simple converging-diverging, straight wall nozzle with A_{exit}/A^* ratio of 1.77, the exit gas temperature will be 1658 K, sufficient to achieve combustion. The ratio of specific heat for this Mach 2 nozzle is predicted to vary from 1.24 at the nozzle inlet ($T_0 = 3000$ K), increase to 1.31 at the throat (2642 K), and reach a value of 1.5 at the nozzle exit. The mass flow rate for this nozzle, operating with a stagnation pressure of 2 atmospheres and an source

temperature of 3000 K, is 50.4 gm/s. The hydrogen gas is to be injected with a 10 ms pulse width at a 10 hz repetition frequency through a slit nozzle located just below one of the longer length nozzle exit edges.

Intrusive diagnostics are not appropriate for accurately measuring these reactive (turbulent) flow properties. Laser-based diagnostics will be utilized to characterize reactive flow properties in the RF heated system. Quantitative concentration profiles will be obtained using planar laser-induced fluorescence (PLIF) on combustion-generated species such as the hydroxyl radical (OH) or nitrous oxide (NO). The dye lasers used to excite these radicals generally have short pulse lengths (5-10 ns). Such short pulse lengths coupled with short fluorescence emission lifetimes allow flow measurements with a high degree of spatial and temporal resolution. It is possible to freeze fast moving features present in supersonic flows. For example, Fig. 7 shows a PLIF-based image of a cold, non-reacting supersonic shear layer. This shear layer was formed by the merging of two supersonic, inert gas (argon and helium) streams. What is noteworthy about the image is the large scale structures evident in the shear layer between the streams. Such structure is evidence of increasing cross stream mixing.

In addition to the concentration diagnostics, a temporally resolved, two dimensional, velocity measurement technique is being developed using Doppler shifted LIF signals. This velocity diagnostic is a modification of an approach documented by Paul, Lee, and Hanson⁸ and is specific to NO. Temperature measurements by such well established methods as coherent anti-Stokes Raman spectroscopy (CARS) are also being considered for use in examining the reacting flows.

Summary

A novel approach to generating high Mach number flows is described. This experimental, supersonic flow system uses gas from an inductively-coupled radio frequency (RF) plasma torch as the high enthalpy source for subsequent nozzle expansion. The absence of electrodes to sustain the plasma discharge minimizes contamination. The resulting high speed flows represent ideal mediums to unambiguously characterize the influence of chemistry on fluid/gas dynamic processes.

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Figure Captions

- Fig. 1. Diagram of the Los Alamos RF Supersonic Flow System.
- Fig. 2. The Los Alamos Plasma Tube.
- Fig. 3. Minimum Sustaining Power for Inductively Coupled Plasma Torches as a Function of Operating Frequency for Several Gases.
- Fig. 4. Exploded View of the Mach 2 Nozzle.
- Fig. 5. The Expansion/Combustion Chamber with Heat Exchanger.
- Fig. 6. View of Plasma Tube Coupled to Expansion/Combustion Chamber.
- Fig. 7. Planar Laser-Induced Fluorescence Image of a Non-Reacting Supersonic Shear Layer.

Fig. 1 Los Alamos Supersonic Flow Facility

MINIMUM SUSTAINING POWER FOR INDUCTION ARCS

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