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EVALUATION OF CANDIDATE WORKING FLUID FORMULATIONS FOR THE ELECTROTHERMAL - CHEMICAL WIND TUNNEL

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ABSTRACT

The objective of this research is to evaluate various candidate chemical formulations as a precursor for the working fluid to be used in the electrothermal hypersonic test facility which was under study at the NASA LaRC Hypersonic Propulsion Branch, and to identify the formulations which would most closely satisfy the goals set for the test facility.

Out of the four tasks specified in the original proposal the first two, literature survey and collection of kinetic data are almost completed. The third task, work on a mathematical model of the ET wind tunnel operation, was started and concentrated on the expansion in the nozzle with finite rate kinetics.

OBJECTIVES

The objective of this research is to evaluate various candidate chemical formulations as a precursor for the working fluid to be used in the electrothermal hypersonic test facility which was under study at the NASA LaRC Hypersonic Propulsion Branch, and to identify the formulations which would most closely satisfy the goals set for the test facility.

WORK DONE IN THE FIRST SIX MONTHS OF THE PROJECT

Out of the four tasks specified in the original proposal the first two are almost completed. The third task, work on a mathematical model of the ET wind tunnel operation, was started and concentrated on the expansion in the nozzle with finite rate kinetics. The work that has been done in the first six months of the project is summarized below.

Task 1: Literature Survey

A thorough survey of the relevant literature has been done. Some highlights are given below:

NASA/LaRC Studies: In 1988 NASA LaRC Hypersonic propulsion Branch has initiated a study to conceptually define a facility which will extend their range of ground testing capability from Mach 7 flight enthalpy simulation to conditions typical of atmospheric flight at Mach numbers up to 12.

For this study the facility goals have been defined in the following order of priority[1]:

1. The facility should provide a steady flow of test gas (21% O_2 by volume) for 10 to 40 seconds at Mach number 10 to 12 (enthalpy 2000 - 3000 Btu/lb) with a test core cross sectional area of 24 x 24 inches and at a Mach number which is 70% of the simulated flight Mach number and with a stream total pressure of at least 5000 psia (approximately 35 lb/s) and, as a goal, a maximum of 15,000 psia (approximately 100 lb/s).

2. The facility should include liquid or gas storage of N_2, O_2 and H_2 to at least 6000 psia and, as a goal, 15,000 psia, a gas heater and a combustor, cooled nozzle approach and throat sections, nozzle expansion sections (variable exit area) for Mach 6, 7 and 8.4.

3. The facility should provide means to direct connect combustors of a size consistent with the above conditions in unvitiated flows at enthalpies to 1000 Btu/lb and vitiated flows with enthalpies to 2000 - 3000 Btu/lb.

4. The facility should provide the capability to test small scale scramjet engines (approximately 50 to 100 square inch nominal capture area) with a length up to 12 ft. The test cabin should be approximately 8 ft in diameter with a length of approximately 20 ft and incorporate a diffuser water spray intercooler connected to the 70 ft vacuum sphere to be installed at Building 1221 at LaRC in FY89.

Subsequently, the design and pilot scale testing of an electrothermal wind tunnel was contracted to General Applied Sciences, Inc. GASL has initiated the design of an electrothermal wind tunnel using air-argon mixtures (replenished with oxygen as required) as the working fluid. Their goal was to provide free jet conditions in the facility which will simulate conditions typical of atmospheric flight at Mach numbers up to 20 and also to provide direct connect simulations for the conditions at the combustor inlet corresponding to the above-atmospheric flight conditions[2]. As a result of their analysis of the facility nozzle for the full scale electrothermal wind tunnel, GASL reported the following findings[3]:

1. The flight Mach 10 and 12 free jet and direct connect conditions can be simulated using air with small amounts of oxygen replenishment to obtain 21% O_2 by volume.

2. Flight Mach 16 free jet simulation requires about 20% argon by mass in the test gas to contain the pressure generated in the mixing chamber. A suitable test gas can be obtained by oxygen replenishment. Direct connect test conditions can be obtained using pure air since typical combustor total pressures are substantially lower than those required for free jet simulation. Oxygen replenishment is needed here as well. Static nozzle exit conditions for both free jet and direct connect simulation are close to the desired test conditions.

3. Simulating Mach 20 free jet conditions requires a minimum of 65% argon by mass in the test gas. Due to the high total enthalpy of the gas, oxygen recombination is found to be minimal. The same holds true for simulating direct connect conditions as well. Increasing the amount of argon in the test gas does not lead to additional recombination to O_2. Substantial oxygen replenishment is required to obtain the correct mole fraction of O_2 at the nozzle exit, and results in the formation of equal amounts of atomic oxygen. In addition, static nozzle exit conditions are far from desired test conditions due to chemical freezing. Therefore, obtaining suitable test conditions or a test medium for flight Mach 20 simulation seems unlikely at this point.

4. In all of the above cases, very low nozzle expansion angles (<3 degrees) are assumed to maximize the formation of O_2. This also maximizes the heat transferred to the nozzle walls and hence increases cooling requirements beyond that encountered by facility nozzles in similar facilities.

GASL recommended further investigations in contoured 2-D nozzle chemistry and in the use of more efficient third bodies such as H_2O to promote additional O_2 recombination. Their preliminary design of a pilot facility (1/50th of the full scale facility) showed that the stagnation conditions of 7900 K and 2170 atm with a test gas containing 32% O_2, 66.7% N_2 and 1.3% Ar by mass will produce nozzle exit conditions of 1600 K, .55 atm and a Mach number of 5.8. These are comparable to the combustor inlet conditions corresponding to a flight Mach number of 16 (Mach number 5.38, pressure 0.55 atm, temperature 2050 K). The gas at the nozzle exit contains 21% O_2, 8.4% O, and 5.6% NO by mole. The throat diameter of the nozzle required to produce these exit conditions is only 1.87 mm. GASL made additional calculations to find out if the required throat area could be increased by replacing the nitrogen in the test gas by argon, but this required the addition of 8% more oxygen to the test gas thereby resulting only in a negligible increase in the nozzle throat area. They have also made calculations to predict the nozzle throat surface temperature rise. The results indicated that active cooling (most likely transpirational cooling) will be needed to maintain the wall temperature below the melting point of the material at the throat and throughout the entire length of the nozzle. To overcome the limitations imposed by the nozzle size and excessive heat flux, they suggested the reduction of test durations to 50 milliseconds.

The funding of this work has been halted due to the failure of the electrothermal concept to meet the gas composition requirements.

Electrothermal guns: The electrothermal gun research were undertaken mainly at the Ballistic Research Laboratories, FMC Corporation, Pennsylvania State University, and GT Devices. The results have been published in volumes one and three of the proceedings of the 26th JANNAF Combustion Meeting[4].

The electrothermal gun is an advanced concept in which a portion or all of the propulsion energy is provided by a high intensity electric energy source discharged into the gun in the form of a plasma jet. The plasma is generated in a tube, called a capillary, when electrical energy from a pulse forming network is discharged between cathode and an annular anode at the opposite ends of the capillary. The plasma is then accelerated through a nozzle into a mixing chamber containing the working fluid or propellant. If the propellant is a nonreactive fluid, the gun operates as an electrothermal gun. If, on the other hand the propellant reacts exothermically, the gun operates as an electrothermal-chemical (ETC) gun or a combustion augmented plasma (CAP) gun (the latter term is used to describe the specific electrothermal-chemical gun being studied by the FMC Corporation).

A major constraint imposed on the working fluids used in electrothermal guns is that they have low molecular weights and, if operating in the ETC mode, produce low molecular weight products in order to maximize the ballistic efficiency (the ratio of projectile muzzle kinetic energy to the total energy, both chemical and electrical, supplied to the gun). The reason for this is that the kinetic energy of the gases is not transferred to the projectile and therefore wasted. Since in the electrothermal wind tunnel the emphasis is on the gases rather than the projectile, this limitation will not be of concern in the design of the test facility. On the other hand, there is a much stricter constraint on the composition of the product gases since they are required to simulate the atmosphere under high altitude, hypersonic flight conditions.

Another property of the working fluid which requires attention is its heat capacity. Since the plasma is created by the external supply of electrical energy, it is possible to achieve an arbitrarily high energy density in the working fluid. This of course leads to excessively high flame temperatures. Therefore, it is necessary that the heat capacity of the working fluid be sufficiently high to reduce the amount of heat transferred to the confining walls. This is also important in the design of the electrothermal wind tunnel to reduce the cooling requirements for the nozzle, but the requirements placed on the composition of the gaseous products will always be the dominant constraint. Presence of water molecules with high heat capacity and low heat capacity ratio will be desirable for this purpose.

Plasma processes: The ballistic efficiency of a ET or ETC gun is determined primarily by the pressure profile of the gun. This profile is determined, in turn, by the rate of evaporation of liquid or solid propellant, and/or the reaction rate of the working fluid. These rates are strongly influenced by the plasma-propellant interaction. Since the same processes determine the stagnation conditions in an ET wind tunnel, they are also very important for the design of the hypersonic test facility.

Recent research on plasma processes in ET guns was focused on two areas: the experimental determination of plasma temperatures and generation of a model of the plasma process. The preliminary work done at BRL by Bunte and Beyer[5] on laboratory scale plasmas using atomic emission spectroscopy indicate that temperatures around 15,000 K (1.32 eV) exist in the plasmas. In their experiments the power supply was charged to 2000 volts and approximately 2000 amperes of current was delivered to the capillary. Spector et al.[6] also measured the temperature, density and velocity of plasma jets created by high pressure discharges. They used charging voltages between 2 - 10 kV with corresponding peak currents of 3 - 24 kA. They report a typical peripheral temperature of 0.4 eV for the plasma jet.

Although it was reported[7] that a one-dimensional plasma model was successfully developed at BRL, it was not made public. Loeb and Kaplan[8] have developed an analytical model for confined high pressure discharges operating at a quasi-steady state. They obtained equations for plasma temperature, pressure, density, and resistivity in terms of the degree of ionization, the induced current and the capillary dimensions. Their model shows good agreement with the experimental results for 30 - 60 kJ discharge systems. Sheppard and Martinez-Sanchez[9] developed a finite rate model to describe nonequilibrium ionization in plasmas. They found that the nonequilibrium effects will be dominant at the inlet and for the initial ionization process.

Plasma - working fluid interaction: The pressure and temperature profiles in the ET gun are primarily determined by the rate of entrainment of the working fluid by the plasma jet and the rate of energy transfer between the plasma and the propellant. These rates are strongly influenced by the area of the interface between the plasma and the working fluid. Marinos and Kuo et al.[10] experimentally investigated the plasma - working fluid interaction in the chamber of a CAP gun using real time X-ray radiography and direct observation by a high speed camera. Their results showed that the first one to two milliseconds is the most important time period for plasma - working fluid interactions while the combustion process lasts several seconds. Observations at 1ms after ignition show that the plasma jet starts to penetrate into the interior of the working fluid, resulting in a "Taylor cavity". The plasma jet then expands rapidly as it penetrates into the combustion chamber. As time goes on, the plasma cools down, and its energy is transferred to the working fluid. A portion of the condensed phase propellant evaporates and expands radially in a non-symmetric manner. In about 4 to 6.5 ms a large portion of the chamber is filled with the gaseous products. It was also noticed that the plasma - working fluid interface appeared wavy indicating that significant entrainment can be induced by the relative motion of the plasma jet and the working fluid, generating a large interfacial area. The researchers concluded that in modelling the performance of the CAP gun the development of Taylor cavity, the entrainment process, and the pressure variations in the combustion chamber should all be considered.

Gough[11] developed a one-dimensional, lumped parameter model to describe the mixing of plasma with the working fluid. The condensed phase propellant is assumed to vaporize at a finite rate. Only the vaporized portion of the working fluid is assumed to mix homogeneously with the injected plasma. The model applies both to inert and reactive working fluids. The mixture of plasma and the working fluid are assumed to be in thermodynamic equilibrium. The plasma is considered as a source of mass, momentum, and energy in the gas phase balance equations. It is assumed that the mixing length for the plasma is fixed at a user specified value. Ballistic parameters were found to be insensitive to the mixing rate which can be taken to be proportional to the rate of plasma injection.

Gas expansion and ET gun interior ballistic processes: The lumped parameter model of Gough[11] discussed above also gives the breech pressure and the muzzle velocity in terms of the propellant/projectile mass ratio and the rate of mixing of plasma with the working fluid.

Cook et al.[12] of FMC Corp. developed a two dimensional, axisymmetric, interior ballistics code that models a CAP gun using a liquid propellant. In the model the plasma constituents are grouped together with the combustion products and treated as the gas phase while the unreacted propellant formed the liquid phase. In the balance equations, the effect of plasma is accounted for in the source terms. The turbulent part of the viscosity term in the Navier - Stokes equation is described by a zero equation model. It is assumed that the energy from the plasma and reactions is used to increase the gas temperature while the liquid temperature remained constant. An empirical equation is used to describe the combustion energy release rate. The model was used successfully to simulate the operations of the 30 mm and 105 mm caliber guns which are currently being tested at the FMC Corp.

White and Oberle[13] used a constant chamber pressure model to describe the internal ballistics of an electrothermal gun, and they employed the model to evaluate the impact of the condensed phase products on the ballistic performance. They found the specific heat ratio to be an important parameter in the establishment of the chamber pressure and the projectile velocity and concluded that, in the evaluation of the propellants, impetus alone will not be a sufficient criterion and, for this purpose, complete interior ballistic calculations are required. The specific heat ratio is also an important parameter in electrothermal wind tunnels not only in the development of the mixing chamber pressure profile, but also in determination of the magnitude of the required stagnation conditions.

Potential ET gun propellants: A major advantage of ET guns is the separation of the tasks of power generation and gas generation allowing more flexibility in the selection of the propellants to provide reaction products with the required properties. King[14] evaluated several candidate propellant formulations for electrothermal guns using the BLAKE computer code of BRL for thermodynamic calculations and a modified version of a lumped parameter interior ballistics code (IBRGA of BRL) for the determination of breech pressures and muzzle velocities. He concluded that considerable muzzle velocity gains can be obtained relative to a conventional gun propellant by using more appropriate formulations as propellants. This gain is partly due to the higher impetus of formulations producing low molecular weight gaseous products. The possibility of increasing the muzzle velocity by using a specified improved pressure trace was also investigated. In this analysis the flame temperature limit was set at 3400 K and the breech pressure was limited to 350 MPa.

Electrothermal propulsion: Electrothermal propulsion systems can provide a high specific impulse option compared to chemical rockets at the expense of a relatively low thrust. In these systems various different methods are being used to transfer electrical energy to the propellant. Among these recent studies on microwave-plasma electrothermal (free radical) propulsion systems, magnetoplasmadynamic (MPD) propulsion systems and propulsion concepts using combination of electrical energy and chemical energy contain information relevant to the proposed electrothermal-chemical wind tunnel concept.

Hawley and his various co-workers[15,16] have studied the microwave electrothermal thrusters experimentally and theoretically. They developed one and two dimensional models of the reaction zone and estimated the axial temperature and concentration profiles which represented experimental measurements well. They observed significant energy losses through wall recombination. Hawkins and Nakanishi[17] recommend wall site treatments with recombination inhibitors or use of a buffer layer of molecular gas at the wall to increase volume recombination. Since the main objective is to increase the specific impulse, hydrogen is the propellant of choice for these systems.

Jeng and Keefer[18] investigated the effect of finite rate chemistry on the performance of a thruster using laser-sustained hydrogen plasma propellant. They used a Navier-Stokes solver to predict the temperature distribution within the combustion chamber and at the throat of the nozzle, and the JANNAF standard TDK code to calculate two-dimensional nozzle expansion with finite kinetics. They found that for propellant stagnation temperatures greater than

9000 K the recombination of ions and electrons is the rate controlling step, while for lower stagnation temperatures the gas composition is determined by the rate of atomic recombinations.

MPD thrusters were investigated both in the United States and Europe[19,20]. The European effort encompasses the research on pulsed coaxial ablative thrusters using Teflon propellant, MPD arcjets producing mainly electrothermal thrust, continuous and pulsed pure MPD thrusters with electromagnetic accelerating mechanisms, and high power (several hundred kW), continuous, self-magnetic field plasma thrusters. The researchers at the University of Pisa developed a two-dimensional model of the MPD channel including real gas effects and based on a finite-difference scheme. Seikel and Franks[19] proposed a completely magnetically contained electrothermal thruster and pointed out that applied-field thrusters are superior to self-field thrusters with respect to efficiency, electrode wear, and conversion of plasma heating to thrust.

Pollard and Cohen[21] introduced the hybrid electrical chemical propulsion concept. The results showed that by adjusting the ratio of electrical energy (higher specific impulse, lower thrust) to chemical energy (lower specific impulse, higher thrust) the desired performance with respect to the specific impulse and thrust can be obtained.

Alternate concepts for hypersonic test facilities: Currently several alternative methods are available for the generation of the conditions required in a hypersonic test facility. These are listed and discussed in the GASL report[1] prepared for NASA/LaRC. Arc heated facilities are limited to relatively low pressures (currently below 3000psia). Augmenting arc heated facilities with MHD accelerators appears to be a very promising concept. Since the energy is added to a relatively low velocity flow, the necessary stagnation conditions are milder and result in reduced wall heat transfer and test gas dissociation. A theoretical study by Crawford and Rhodes[22] have shown that combustor inlet conditions for hypersonic flight vehicles corresponding to flight Mach numbers up to 25 could be simulated with nearly exact properties. The drawback of this concept is the contamination by the seed (about 1%) which has to be added for the MHD process. The flash tube concept, which uses a slow moving deflageration wave in a driver tube with an open end, has not yet been demonstrated. Impulse facilities do not provide the required test duration. The method preferred in the

GASL concept study was the use of a graphite or zirconia storage heater using vitiated air for high enthalpy runs and unvitiated air for low enthalpy clean air runs.

Task 2: Collection of Thermodynamic and Kinetic Data

Efforts in this area were concentrated on obtaining data for the propellants containing mainly nitrogen, hydrogen, and oxygen such as NH_3 and HAN and those containing a relatively small amount of carbon such as HMX, and RDX. Some alternate oxygen sources such as nitrogen pentoxide and nitrogen dioxide were also considered. The reason for this choice is to keep the composition of the test air as close to that of the high altitude atmosphere as possible and to avoid introducing a large number of foreign atoms such as carbon into the test air chemistry. A list of the literature containing relevant data is provided in Appendix 1. The analysis of the available data is not yet complete. Rather than to include the raw data here we plan to present our results in the next report.

Task 3: Development of a Mathematical Model

At this stage the chemical-electrothermal wind tunnel will be modelled as a mixing chamber connected to an expansion nozzle. Since we expect to take advantage of kinetics to alleviate some of the limitations imposed on the test gas composition by chemical equilibrium the use of finite rate chemistry is important. For this purpose we have acquired the 'GCKP84 General Chemical Kinetics Code" and adapted it to work on our 486 personal computer. The code has been debugged and tested using the case studies provided. We are now ready to start testing the working fluid formulations.

FUTURE WORK

The future work will consist of the following:

1- Analysis of the kinetic and thermodynamic data and their conversion into a format suitable for use with the General Kinetics Code.

2- Evaluation of candidate formulations using the computer model.

3- Modification of model to represent the wind tunnel more closely.

4- Testing of various formulations with the modified model.

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