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A Review of Test Medium Contamination Effects on Test Article Combustion Processes

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Abstract

Aerospace systems currently in operation demonstrate that good, useful results can be obtained from ground testing in existing test facilities. One of the concerns with ground testing is that the thermochemical characteristics of the flight medium, the standard test medium, are different from the thermochemical characteristic of the ground test medium, a non-standard test medium, (NSTM). This paper is concerned with the effects on hypersonic air-breathing propulsion systems that may be a result of the method used to supply the energy necessary for simulation of hypersonic flight in the atmosphere.

A review was begun of published results that address the effects of a NSTM on combustion in the test article. This paper documents the current understanding of the effects of available energy addition processes on the test medium and suggests an approach to make the best possible use of ground test facilities. A second paper is planned to address specific examples.

Review of the literature shows that each case is different and must be analyzed individually. A second observation from the review is that all energy addition methods currently used to simulate hypersonic atmospheric flight create a NSTM. The best solution to the problem of the question of NSTM effects is to be aware of the differences between the flight medium and the NSTM and to know how these differences affect the test results. The most detrimental situation is to be unaware of the differences in test media that affect the results of the test.

Introduction

Duplication of all characteristics of the flight is the goal of testing, but that is usually impossible. Simulation of the characteristics of flight, with duplication of the most important parameters, is usually the best that can be achieved. Proper simulation is an integral part of the development process for any aerospace system. It has been important from the time of the Wright flyer[1] and ever will be. Concerns about the effects of the compromises inherent in simulation, i.e., the parameters not matched, have been an issue from the beginning.

The compromises inherent in experimental simulation can arise from numerous sources: spatial nonuniformity, unsteadiness, mismatched boundary conditions, transient process, differences in physical scale, differences in the test medium, and others. This review is limited to the effects of differences in the test medium and, with the exception of the introduction, it is limited to the effects of the differences in the test medium on the combustion processes in the test article. The test article assumed in this paper is an air-breathing hypersonic propulsion system, a ramjet or scramjet.

NSTM effects on the results from aerothermal test results are documented elsewhere.[2] The possibility of condensation of test facility flows that contain water, a component of all combustion-heated facility flows, is always a concern. The flows considered herein will be assumed condensation-free. Reference 3 is recommended as a starting point for a description of water condensation in test facility flows.

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The paper will discuss the characteristics of the most common energy sources for hypersonic simulation facilities. The effects that the individual energy sources can have on test medium composition and the effect of a NSTM on test article combustion will be described. An attempt is then made to unify the understanding of the effects, based on simplified explanation of test article combustion. The conclusions and recommendations complete the paper.

Arc Heated Facilities

Arc heaters provide the highest enthalpy of any currently operational quasi-continuous flow device. Enthalpies corresponding to atmospheric flight at about Mach 12 can be generated for periods of minutes. Arc stability currently limits the total pressure to less than about 200 atm, limiting the available altitude simulation at high flow Mach numbers.

The arc process generates atomic species and ionized molecular and atomic species. Local equilibrium in the stilling chamber down stream of the arc is a good assumption. Residual temperature gradients from the arc process mean that the equilibrium condition is not uniform. Thermodynamic conditions change too rapidly in the expansion through the nozzle for the collisional processes to maintain chemical and local thermal equilibrium. The result is a test medium with supra-equilibrium levels of oxides of nitrogen, primarily NO. The NO is thermodynamically similar to air and has a vanishingly small effect on aerothermodynamic measurements unless some chemical effect, like surface catalicity, is important.

NO can affect combustion processes in two ways. It removes some oxygen from the reaction, altering the stoichiometry of the reaction zone, and NO can participate in the chemical reactions. Numerous studies of the possible effects of NO on combustion have been published.[4-6] The consensus appears to be that NO can accelerate or retard hydrogen-air ignition, depending on concentration, equivalence ratio, pressure, and temperature, and that the effects can be significant for some cases.

The effect of NO contamination on hydrocarbon reactions was studied in Ref. 5. The conclusion stated by those authors was that the effects were too complicated for a simple summary. That is a safe conclusion in the case of hydrogen reactions also.

Atomic oxygen may also exist in the test medium as a result of incomplete recombination in the stilling chamber and in the nozzle. The effects of atomic oxygen, always a catalyst, will be discussed in a subsequent section.

The internal energy modes of the test gas may not be in equilibrium with the translational mode as a result of the expansion. This problem will be discussed in more detail in a succeeding section.

The other contaminant present in arc heated flows is traces of copper and its oxide from the electrode. Relatively little work has been done on the chemical effects of copper but it is believed to be essentially inert. The effects of copper on other processes, eg. heat transfer, depend on the nature of the contamination.

Combustion Heated Facilities

Many facilities use instream combustion of hydrogen or a hydrocarbon to produce a high enthalpy test medium. Such facilities have many practical advantages, including long, quasi-continuous, run times, comparatively low initial and operating costs, and simple operation. A drawback of combustion heated facilities is that they are limited to simulating flight at Mach numbers of about 8 or less if temperature is to be matched. Another major concern is that the test medium is significantly different from the flight medium. The primary products of combustion are H_2O and if a hydrocarbon fuel is used, CO_2. The minor constituents can include OH, O, H, CO, oxides of nitrogen, CH_x, and other fragments of the fuel. The concentrations of these species depend on the details of the combustion process. Equilibrium calculations at the heater conditions provide a lower bound for the concentrations of the minor species, but no realistic estimate for the upper bound of these concentrations can be made. The minor species are present in higher than equilibrium concentrations in the reaction zone of the heater. The final concentration depends to a great extent on the mixing and

quenching that occurs as the facility combustion processes undergoes the final relaxation to equilibrium. Presuming proper oxygen replenishment, the difference is equivalent to replacing some of the nitrogen with the products of combustion, eg. air is nominally 78-percent N_2, 21-percent O_2, and 1-percent Ar, and a combustion heated test medium might be 69-percent N_2, 21-percent O_2, 1-percent Ar, 4-percent CO_2, and 5-percent H_2O.

Carbon dioxide, CO_2, and H_2O in the test medium affect test article combustion in at least two ways. Their higher heat capacity, compared to the nitrogen they displace, reduces the temperature increase during combustion. The reduced temperature can reduce the reaction rate, and can increase the ignition delay at low initial temperatures, < 1250 K, for hydrogen - oxygen reactions. At higher initial temperatures, the effect is reduced. The effects of H_2O on hydrocarbon reactions are too varied for simple generalization.[5]

Recent English language summaries of Russian hydrogen fueled scramjet research indicate evidence that CO_2 and H_2O affect ignition delay only when they represent a significant fraction, > 15 percent by mass, of the flow but that trace amounts of O, H, and OH significantly reduce the ignition delay.[7]

The sensitivity of all hydrogen or hydrocarbon combustion systems to the initial concentrations of OH, O, and H is well known. Specific examples of the sensitivities will be given later. The effects of CO, CH_x, and other fuel fragments are less clear. CO acts as an additional fuel in the test medium but appears to have little direct effect on the kinetics.

Chinitz, et. al.,[5] in a reaction set used for diesel ignition studies, list several individual reactions involving CH_2 that could also be important in hydrogen-air reactions. Other potentially important reactions involving hydrocarbon fragments are cited elsewhere.[8]

One recent case[9] illustrates the problem. Repeat tests using the same hardware and the same test article fuel, ethane, were made in two different combustion heated facilities. The first tests used Jet-A as the fuel in the facility heater

and the second tests used hydrogen as the fuel in the facility heater. The efficiency of the Jet-A heater was stated to be 95 percent and the efficiency of the hydrogen heater was stated to be 100 percent. The definition of the efficiency and the nature of the inefficiency were not given in the report. The second test, (hydrogen heater), showed markedly lower test article performance than the first, (Jet-A heater). Test article performance with the hydrogen heater was restored to levels observed with the Jet-A heater through the inclusion of a small amount of a pyrophoric, (silane, SiH_4) in the test article fuel. The interpretation by this reviewer, not stated by the original author, is that the 5-percent inefficiency observed with Jet-A was in the form of some methane radicals, CH, CH_2, and CH_3, and that they acted as a catalyst for the subsequent ethane reaction in the test article. This interpretation is consistent with the understanding of hydrocarbon chemistry.[8, 10]

The conclusion that should be drawn from this example is that the details of the facility combustion process are important to proper interpretation of the test results.

Two possible misinterpretations of this example should be put to rest immediately. The first misinterpretation is that combustion heated facilities should not be used for propulsion research. This is incorrect. Proper understanding of the effects of all energy addition mechanisms is crucial to the understanding of the simulation results. The second misinterpretation is that a heater using one type of fuel is inherently better than a another heater using a different type of fuel. Each possible fuel has its advantages and disadvantages but the effects of the NSTM generated by the heater must be considered in any case.

Shock/Expansion Facilities

Shock tubes can be used to produce flows with enthalpies comparable to the energy of orbital speeds. The flow duration is short, microseconds to milliseconds, and many hardware and test medium contamination problems associated with the temperatures and pressures exist. Reference 11 is recommended for an introduction to the subject. It gives the operating principles of the devices and alludes to some of the problems.

Reflected shock tunnels generate a high-pressure high-temperature stagnant gas volume at the closed end of the driven section of a shock tube. The gas that becomes the test medium is compressed, heated, and accelerated by the passage of an incident shock. The gas is further compressed and further heated, and decelerated by the passage of the reflected shock. That gas is expanded through a converging-diverging nozzle when a second diaphragm upstream of the throat opens. Quasi-steady flow is established in the nozzle and over the test article. Conical nozzles are typically used but contoured nozzles can be employed if more uniform flow is desired.

The key point, from the standpoint of test medium effects, is that the test flow is accelerated from an equilibrium condition at the stagnation condition, total energy and pressure. The process of expansion through the nozzle will cause a deviation from local equilibrium because the thermodynamic variables change faster than the chemical process can react. Eventually, when the density and temperature are reduced sufficiently, the chemical reactions will essentially cease and the composition of the flow will not change.

The most significant effect of the cessation of reaction is that a significant fraction of the oxygen present may be atomic oxygen, O, rather than molecular oxygen, O_2. The presence of atomic oxygen, on the order of several mole percent, represents a significant departure from equilibrium. That departure means that the temperature is not a good indicator of the energy level of the test medium. The most significant effect of the atomic oxygen can be on the subsequent chemical reactions. Specific examples will be given later. Significant amounts of NO can also be present in the test medium.

Shock-expansion tunnels reduce the effect of oxygen dissociation by expanding the gas after it has been processed by a single shock wave. There are many practical problems, flow uniformity and flow duration, for instance. The level of oxygen dissociation is reduced, in some cases, to a sufficiently low level that the test medium energy is well represented by the temperature using an equilibrium assumption. The catalytic effect of the atomic oxygen can still be significant.

Jachimowski[12] developed a model to account for the effect of oxygen dissociation on the results from combustion tests in a reflected shock tunnel or a shock expansion tunnel. The method included finite rate chemistry effects. Parameters in the model were adjusted to obtain an axial pressure distribution that closely resembled the axial pressure distribution observed in the test. The model was then used to predict the performance in the flight medium. Jachimowski determined that reducing the initial oxygen concentration by a factor of about four could compensate for the effects of oxygen dissociation. Dilution of the hydrogen fuel with helium, about 50 percent, could also be used to compensate for the effects of oxygen dissociation. Both of these compensation mechanisms affect the energy release of the hydrogen reaction. The temperature before reaction for the case reported was sufficiently high, > 2200 K, that the atomic oxygen concentration had little practical effect on the induction time.

The work reported was well done and informative. Detailed review indicates that the results obtained are strongly dependent on the assumptions made in the model and that the specific conclusions, eg., a factor of four, 50 percent, are probably only applicable to the single test point cited in the work. The approach has more general applicability.

Thermal Storage Facilities

Thermal storage heaters are often suggested as the solution to the problem of test medium contamination. Thermal storage heaters do eliminate some of the problems inherent in many heat transfer methods of enthalpy addition. Specifically, the surfaces across which the heat is transferred need not be structural members and the surfaces can be made resistant to oxidation. Thermal storage heaters do introduce contaminants into the test medium.

Thermal storage facilities generate solid particulate in the test medium. The source of the solid particulate is surface fretting, caused by relative motion between the surfaces, of the energy storage medium. The relative motion is caused by thermal expansion. The motion can also be caused by mechanical motion induced by the airflow. Fracture

due to thermal stress is also a possibility. Ample evidence exists that the flows do contain solid particulate, (polished surfaces develop a dull appearance after exposure to the flow, sharp leading edges develop radii, etc.), but the nature and extent of the contamination is difficult to determine. Careful design and operation can reduce, but not eliminate, the problem of solid particle contamination.

Solid particulate impact is a good mechanism for surface heat transfer augmentation. The augmented heat transfer could produce a local hot spot that could serve as an ignition source. Direct participation of the solid particles in the chemical reactions is unlikely. The particles are small, they are cooled to the freestream temperature, and they are chemically inert.

The air is in equilibrium at the stilling chamber conditions. Thermodynamic conditions change too rapidly in the expansion through the nozzle for the air to stay in thermal equilibrium.[13] This can produce a supra-equilibrium vibrational energy level in the gas. Thermal non-equilibrium is a possibility in any expansion from high enthalpy. The water present in the test medium of a combustion heated facility effectively catalyzes the vibrational to translational energy exchange and reduces the level of, but does not necessarily eliminate, the nonequilibrium vibrational energy of the diatomic molecules. The details of the effect(s) of the supraequilibrium vibrational energy level are unknown at present. Reasons for concern about the effect of the thermal nonequilibrium are given next.

Thermal Non-equilibrium Effects

The dissociation rates of O_2 measured in a variety of well conducted experiments differed by more than the combined uncertainty of the experiments. The discrepancy lead to significant differences in the predicted behavior of air down stream of a strong shock. The resolution of the discrepancy is well documented in Ref. 14 and the references it contains. The result of the analysis is that the vibrational energy state of the molecules is an important consideration in the dissociation rate.

The analysis documented in Ref. 14 applies to initially cold gas in equilibrium that is heated by a strong shock. The vibrational energy excitation lags the translational energy excitation downstream of the shock. The population of molecules in the vibrational states above the ground level is less than it would be if the gas were in thermal equilibrium. The reduced population retards dissociation.

The situation considered here is the reverse. The nozzle expansion creates a gas in which the population of molecules in the states above the ground state is greater than it would be if the gas were in thermal equilibrium. The populations are only slightly greater than the equilibrium levels based on the total conditions, so the effect of the excited states on the energy balance is small. The small increase in the population of excited states may enhance oxygen dissociation. As will be shown later, small increases in oxygen atom concentrations can have dramatic effects on the induction time, so the effects of small deviations from equilibrium might be important. Quantitative knowledge of the effect is missing at present.

Much work has been done to address the coupling of vibrational excitation and dissociation. Dramatic increases, (a factor of 500), are cited for some molecules for some circumstances.[15] No report of work directly applicable to the present case was found. The field of state-specific reaction rates is an active research area. The details of the relevant process may be known in the near future. Anything that alters the rate of oxygen dissociation will have an effect on the subsequent chemical reactions. Specific examples will be given later.

A subequilibrium vibrational energy in oxygen is known to retard the reactions that dominate the induction period.[16] The magnitude of the effect of a supraequilibrium level of vibrational energy is not known.

Summary of Various Types of Energy Addition

The purpose of the review documented by this report was to assess the effects of typical NSTM on combustion in a test article. The different types of NSTM produced by different energy addition methods and their impact on the subsequent combustion have been described above. The critical question in each case is how the NSTM affects the test

results. That question is the point at which the effects of all the different types of NSTM begin to converge. One statement, "Combustion is controlled by initial concentration of free radicals or the subsequent ability of the mixture to generate them." from Ref. 5 provides the best summary of the possible effects. A brief review of applicable concepts from combustion chemistry will be given next.

Review of Chemistry

Reference 8 and similar texts are recommended for a general introduction to the topic of combustion chemistry. A brief explanation of terms will be given here. A combustion reaction is the process of transforming atoms from one configuration to another, more stable, configuration with the liberation of thermal energy. The reactions considered here can be divided into three sequential steps, induction, heat release, and equilibration. The choice of the definition of those steps is arbitrary. The definition used in this paper is illustrated in Fig. 1 and will be discussed below.
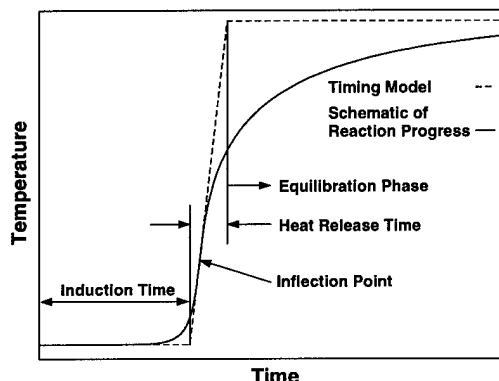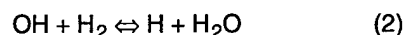

Fig. 1. Induction time and heat-release time definition.

Consider the reaction of hydrogen and air. The ignition phase of the reaction is dominated by the build up of free radical species, OH, O, H. The chain branching reaction ,
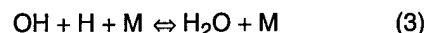
$$H + O_2 \Leftrightarrow OH + O, \tag{1}$$

considered to be the most important reaction in combustion[10] is representative of the induction phase. The temperature change is relatively small and little of the product species are formed during the induction phase.

The heat release is characterized by the formation of a significant amount of the final products and the depletion of the major part of the reactants. The chain propagating reaction

$$OH + H_2 \Leftrightarrow H + H_2O \tag{2}$$

is typical of the heat release phase. The equilibration phase is characterized by three-body recombination reactions like

$$OH + H + M \Leftrightarrow H_2O + M \tag{3}$$

and by the slow reactions like dissociation of N_2 and formation of oxides of nitrogen.

The following definitions, illustrated in Fig. 1, are made to quantify the effects to be discussed later. The heat release time, or reaction time, is equal to the temperature rise, final - initial, divided by the maximum temperature gradient. The induction time is the time from the beginning of the reaction to the point where the maximum tangent to the temperature versus time curve extrapolates to the initial temperature. The equilibration phase is after the end of the heat release phase. During the equilibration phase, the temperature change is comparatively modest and the concentrations of the major species do not change significantly. The concentration of free radicals decreases and the trace species are formed. The effect of the definition used herein is to replace the sigmoid like time-temperature curve with three straight line segments.

Analogous definitions can be constructed based on disappearance of reactants or appearance of products. Many other definitions of the characteristic times of the reaction are in common use. Care must be exercised when comparisons from different works are made since different definitions can produce different conclusions.

The "chemistry set" necessary to describe the progress from reactants to products consists of the collection of elementary reaction steps, like Eqs. 1-3, the rates of those steps, and thermodynamic properties of the species involved in the reaction. Errors in any one of the three components will produce erroneous and possibly misleading results.

Even the best chemistry sets are applicable to limited ranges of conditions. A set appropriate to one pressure may not be appropriate to another. Due diligence must be exercised in combining parts of several reaction mechanisms since it is the interaction of all the parts that determines the result. Except in the simplest cases, it is impossible to prove that any given reaction mechanism is unique. The parameters that are used to represent the rates for the individual reaction steps must be evaluated and combined with great care. Similarly, the initial composition can determine which elementary steps need to be included and which can be neglected. The reaction set and the reaction rates are a mathematical model of the physical process. Determining the appropriate components of that mathematical model is the most difficult step. [17]

Sample Case

Particular types of NSTM generated by different energy addition methods have been discussed. The effects have been described in qualitative terms. The results from the basic case, representative of flight, will be described and then the variations caused by the different NSTM will be given. The effects of all the NSTM discussed depend on the thermodynamic state of the test medium. Conclusions drawn from the sample case given below do not necessarily translate directly to another temperature, equivalence ratio, or pressure. As will be shown, the effects are generally nonlinear so superposition is not appropriate to assess the combined effects.

The chemistry set used for the sample case discussed next consists of the reaction steps and rates from Ref. 18. The chemistry set was used with the chemical kinetic code documented in Ref 19. The case chosen for demonstration was an initial temperature of 1000 K, a constant pressure of 1 atmosphere, and an equivalence ratio, based on chemical valences, of 1.0. The fuel was gaseous hydrogen and the oxidizer was nominally 20.95-percent molecular oxygen, 0.934-percent argon, 314 ppm CO_2 and the balance, nominally 78 percent, nitrogen. The induction time, τ_i, was $1.93 * 10^{-4}$ sec and the heat release time, τ_{hr}, was $2.25 * 10^{-5}$ sec. These values compare favorably with other published data, Ref. 6 for instance.

An initial concentration of radicals, specifically O, H, and OH in this case, can dramatically reduce the induction time. No reliable means of detecting hydrogen atoms is known, but oxygen atoms and OH can be measured at concentrations of 10^{12}/cc.

The induction time calculated for six cases with varying initial concentrations of atomic oxygen are show in Fig. 2. The effect is nonlinear and the largest relative effect is as a result of the initial introduction of atomic oxygen. The effect of the atomic oxygen concentration on the heat release time is insignificant. The concentrations of the radicals during the heat release phase are orders of magnitude larger than the values assumed to generate Fig. 2. The radical concentrations during the heat release are independent of the initial radical concentrations. Those two facts account for the observed insensitivity of the heat release time to initial atomic oxygen concentration. Many other properties affect the heat release time but not radicals at the concentrations examined here.
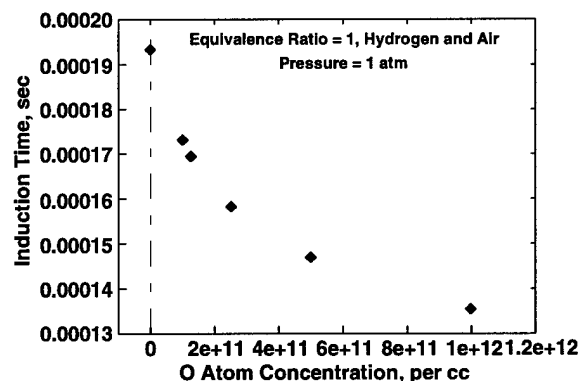

Fig. 2. Effect of initial O atom concentration on induction time.

Several other cases were calculated with varying amounts of radicals. The results are summarized in Table 1.

The effect of any of the chosen radicals is similar to the effect of atomic oxygen. The reduction shown in Table 1 and Fig. 2 are believed to be real. Their significance to the test result depends on the geometry of the test article and the nature of the test. Another significant result is that concentrations an order of magnitude below the measurement threshold can cause an effect. This is a potentially troublesome situation. It means that

something that cannot be measured may affect the test results.

Table 1. Effect of Initial Radical Concentration on Induction Time and Reaction Time

Concentration,* 10^{-12}/cc	Species	τ_i, μsec	τ_{hr}, μsec
0	-	193	22.5
0.1	N	176	22.5
0.1	OH	183	22.4
0.1	H	183	22.5
0.1	O	173	22.5
0.125	O	170	22.5
0.25	O	158	22.5
0.5	O	147	22.5
1.0	O	136	22.4
1.0	H	146	22.4
1.0	OH	146	22.4
2.0	O & H	128	22.4
2.0	O & OH	128	22.4
2.0	H & OH	134	22.4
3.0	O, H, & OH	124	22.4

One final observation is the catalytic effect of nitrogen atoms on the reaction. Their effect is primarily through their ability to form NO and O when they react with O_2.

The effect of small variations in initial temperature on the induction time are shown in Fig. 3. A small difference in temperature can make a significant difference in the induction time at these conditions. The difference is more than an order of magnitude over the temperature range shown here. At higher temperatures, the induction time is much
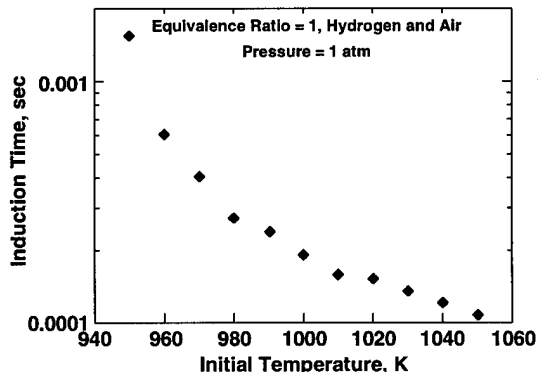

Fig. 3. Effect of initial temperature on induction time.

shorter and the effect of differences in initial temperature are much smaller. The sensitivity of induction time to initial temperature points out a potential problem for test facilities with nonuniform temperature distributions.

The observed trend is a result of the Arrhenius form assumed for the reaction rates of the dominant reactions. The same trend has been suggested by analytic studies based on simplified reaction mechanisms.[20]

As with the radicals, the initial temperature has a very small effect on the heat release time, about 10 percent, over the range shown. The insensitivity of heat release time to initial temperature is consistent over a wide temperature range.

The reaction rate assumed for specific reactions can have significant effects on the induction time. The effect on induction time of variations in the rate of the reaction, $H + O_2 \Leftrightarrow OH + O$, is shown in Fig. 4. The induction time is reduced by about a factor of two when the reaction rate is doubled. As is obvious from Fig. 4, anything that alters the dissociation rate of O_2 can have a dramatic effect on the induction time. The effect on the heat release time is much more modest, about 15 percent change over the whole range shown.
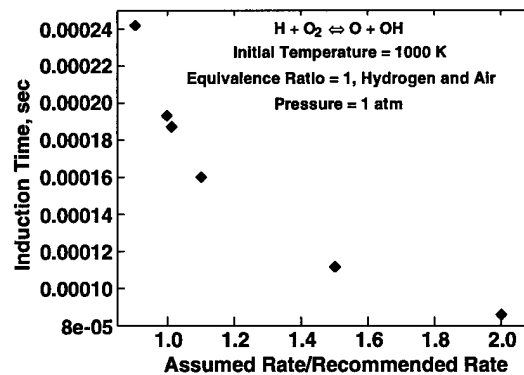

Fig. 4. Effect of variation in reaction rate.

The range of values of the rate for the reaction from nine reputable sources are shown in Fig.5. The range is about a factor of three at 1000 K and a little more than a factor of two at 2000 K. The last figure is not strictly related to the effects of a NSTM. Figures 4 and 5 address the concern of the

proper selection of the elementary reaction steps and the rates at which those steps occur.
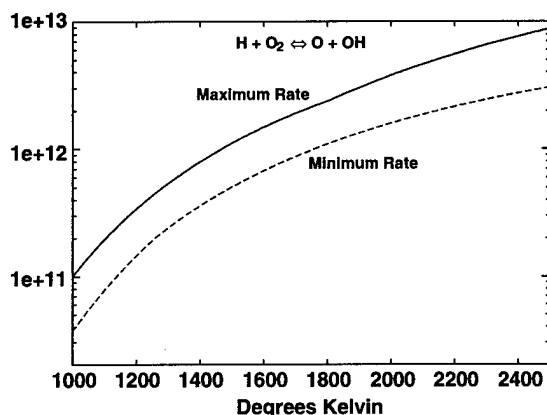

Fig. 5. Various published reaction rates.

The effect of NO concentration on induction time is shown in Fig. 6. The trends shown in Fig. 6 agree with many statements found in the literature, but they do not agree, quantitatively, with the results from well conceived and executed experiments.[6] One possibility is that some unmeasured or uncontrolled parameter affected the experimental results. Another possibility is that the chemistry set chosen here is not appropriate to the study of the effects of NO on induction time. If a mathematical model is to be used to study some phenomenon in a combustion system, then the mathematical model must contain an accurate representation of the physical process that produce that phenomenon.
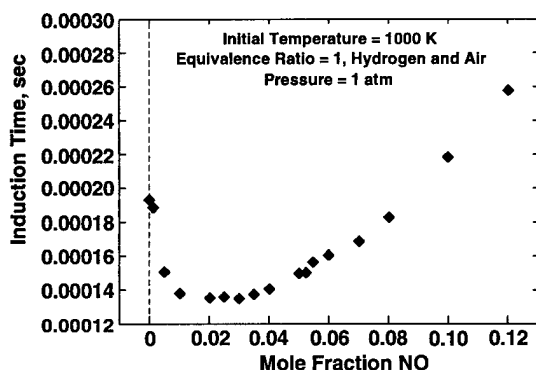

Fig. 6. Effect of NO concentration on induction time.

Summary

The kinds of differences in test medias caused by the common types of enthalpy addition have

been discussed. Their possible effects on test article combustion have been described and, where possible, specific examples have been given. It is apparent that each case must be considered separately. The necessity to test in an adulterated test medium adds another significant step to the test planning and to the test data interpretation. The proper approach is summarized in Ref. 5, "... careful pre- and post- test analyses using validated chemical kinetic mechanisms, will be required to ensure that wind tunnel experiments using hydrocarbon fuels achieve the results desired and that the data obtained are correctly interpreted." The conclusion applies to any reactive system, not just hydrocarbons.

Conclusions and Recommendations

The following conclusions were reached as a result of this brief review.

1. Testing in an adulterated test medium is inevitable for simulation of hypersonic flight. All available facilities must be used, based on their advantages and cognizant of their limitations.

2. Each case is different and each test must be planned, executed, and analyzed with the unique aspects of the test and the test medium in mind.

3. Much work remains to be done to resolve the questions of test medium effects. First, better understanding of the physical processes must be developed. Second, verified mathematical models of the physical processes must be developed so that CFD can better support ground testing. Third, instrumentation must be improved and more use of existing instrumentation must be made to define the input to the test article.

AEDC is continuing the effort begun last year and documented in this paper to better understand how the test media produced affect the test results sought. The future developments will be presented in a subsequent paper.

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13. ABSTRACT (Maximum 200 words)
Aerospace systems currently in operation dem-onstrate that good, useful results can be obtained from ground testing in existing test facilities. One of the concerns with ground testing is that the ther-mochemical characteristics of the flight medium, the standard test medium, are different from the thermochemical characteristic of the ground testtmedium, a non-standard test medium, (NSTM). This paper is concerned with the effects on hypersonic air-breathing propulsion systems that may be a result of the method used to supply the energy necessary for simulation of hypersonic flight in the atmosphere.

A review was begun of published results that address the effects of a NSTM on combustion in the test article. This paper documents the current understanding of the effects of available energy addition processes on the test medium and suggests an approach to make the best possible use of ground test facilities. A second paper is planned to address specific examples.

Review of the literature shows that each case isdifferent and must be analyzed individually. A second observation from the review is that all energy addition methods currently used to simulate hypersonicatmospheric flight create a NSTM. The best solution to the problem of the question of NSTM effects is to be aware of the differences between the flight medium and theNSTM and to know how these differences affect the test results. The most detrimental situation is to be unaware of the differences in test media that affect the results of the test.

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