JOURNAL OF PROPULSION AND POWER
Vol. 21, No. 3, May–June 2005

Autoignition of Kerosene by Decomposed Hydrogen Peroxide in a Dump-Combustor Configuration

J. C. Sisco,* B. L. Austin,† J. S. Mok,* and W. E. Anderson‡
Purdue University, West Lafayette, Indiana 47907

In staged-bipropellant rocket combustors that use decomposed hydrogen peroxide as the oxidizer, a liquid fuel is injected into the hot decomposition products comprising oxygen and water vapor. For a well-designed combustor, the oxidizer is at a sufficiently high temperature to vaporize and to autoignite the liquid fuel; however, experimental autoignition data in key chamber contraction ratio and propellant equivalence ratio ranges are missing. In this study a transverse injector was used in a dump-combustor configuration to investigate the autoignition characteristics of JP-8 in decomposed hydrogen peroxide, specifically fuel-rich autoignition limits at contraction ratios less than 6 and with high hydrogen peroxide concentrations. The chamber contraction ratio was varied between 3 and 5 to evaluate the effects of chamber gas Mach number (0.45 and 0.27), and the hydrogen peroxide concentration was varied from 85 to 98% by weight to evaluate the effects of oxidizer temperature. Three regimes were noted: strong, weak, and no autoignition. Chamber pressure oscillations with a dominant frequency between 27 and 47 Hz occurred in the weak-autoignition regime. Results showed that as hydrogen peroxide concentration and/or contraction ratio was increased the equivalence ratio that defined the autoignition boundary increased as well. At a contraction ratio of 3.0, no autoignition was achieved at equivalence ratios of 1.37 and above using 85% hydrogen peroxide, but with 98% hydrogen peroxide autoignition occurred at an equivalence ratio as high as 2.06. When the contraction ratio was increased to 5.0, autoignition was achieved at an equivalence ratio of 1.38 using 85% hydrogen peroxide. These data provide a starting point for the development of an accurate autoignition model and an empirical basis for the design of efficient combustors.

Nomenclature

A = cross-sectional area
BG = blockage ratio, A_{st}/A_c
C^* = characteristic velocity
D, d = diameter
E_a = global activation energy
h = rearward-facing step height
L^* = chamber characteristic length
p = static pressure
Q = momentum ratio, $\rho_f V_f^2/\rho_g V_g^2$
R_u = universal gas constant
T = static temperature
V = velocity
W = concentration
x = axial coordinate
y = transverse coordinate
ρ = density
τ_i = ignition delay
τ_{st} = shear-layer residence time
ϕ = equivalence ratio

Subscripts

af = adiabatic flame
c = chamber
c2 = chamber (second axial location)
d = decomposition
fu_inj = entrance to fuel injector manifold
f = fuel
g = gas
in = inlet (entering rearward-facing step)
o = orifice
opt = optimum
st = rearward-facing step
th = throat

Introduction

BIPROPELLANT chemical propulsion systems that use hydrogen peroxide, H_2O_2, as the oxidizer and a liquid hydrocarbon fuel are suitable for a variety of applications.[1] Although this propellant combination is one of the oldest in modern rocketry, with a history extending back to World War II, there is a lack of basic understanding particularly with respect to the injector. The injector design is key because it controls the performance and heat transfer characteristics of the combustor as well as whether combustion instabilities will occur.

These bipropellant systems either deliver the peroxide as a liquid directly into the combustion chamber or catalytically decompose the peroxide before its injection into the main combustion chamber; all systems that have flown have used the latter method, whereby a catalyst bed is used to decompose the peroxide into a high-temperature oxidizing gas mixture of oxygen and steam. A number of benefits result from this approach. Simpler injection systems are possible, because fuel only is injected at the downstream location, and the high momentum of the gas stream rapidly atomizes the liquid fuel. Another beneficial result is that the temperature of the oxidizer is higher than the autoignition temperature of the fuel; thus, a separate ignition system can be eliminated.

However, a few challenges do exist with these types of combustors. The injector and combustor designs must ensure the appropriate flow conditions for ignition and flame holding. Also, because the optimal theoretical performance of the peroxide/kerosene propellant combination is at an oxidizer-to-fuel (O/F) mass ratio of about 8 (depending on the peroxide concentration that is used), it is difficult to completely mix the relatively small amount of fuel with

---

Presented as Paper 2003-4921 at the AIAA/ASME/SAE/ASEE 39th Joint Propulsion Conference, Huntsville, AL, 20–23 July 2003; received 17 September 2003; revision received 26 September 2004; accepted for publication 26 September 2004.

*Graduate Student, School of Aeronautics and Astronautics. Member AIAA.

†Formerly Graduate Student, School of Aeronautics and Astronautics; currently General Manager, IN Space, LLC, West Lafayette, IN. Member AIAA.

‡Assistant Professor, School of Aeronautics and Astronautics. Member AIAA.

Table 1 Summary of operating parameters of some of the past staged-bipropellant combustors using hydrogen peroxide and kerosene-based fuels

Parameter	Walder and Broughton[2]	Gamma[3,4]	LR-40[5]	Wu et al.[6]	Upper stage flight experiment[7]	Muss et al.[8]
W (%)	80	85	90	85	90	90
Fuel	Kerosene	Kerosene	JP-5	JP-8	JP-8	JP-8
ϕ	0.95	1.04	1.14	0.94	1.70	1.34
CR	6.5	7.7	>10.0	7.1	7.1	5.3

Table 2 Comparison between catalyst beds used during testing; design operating conditions and geometry are indicated

Catalyst bed	CB-1	CB-2
H_2O_2 concentration	Up to 92%	Up to 98%
Mass flow rate, kg/s (lbm/s)	1.14 (2.50)	1.14 (2.50)
Bed loading, g/cm$^2 \cdot$ s (lbm/in$^2 \cdot$ s)	27 (0.38)	56 (0.80)
Internal diameter, cm (in.)	7.4 (2.9)	5.1 (2.0)
Exit diameter, cm (in.)	7.4 (2.9)	4.4 (1.8)

the oxidizer. The design of the injector/combustor must promote both autoignition and good mixing.

Historically, successful autoignition was achieved by using relatively high chamber contraction ratios (CRs; A_c/A_{th}), typically around 7, compared to more typical CRs of 2 to 3 for most bipropellant systems. The CR is defined as the ratio of the chamber cross-sectional area to that of the throat. Table 1 summarizes combustor design parameters from a number of past systems.[2–8] The higher CR allows lower chamber flow Mach numbers and longer residence times for ignition. The high CRs, of course, result in heavier combustors and greater chamber wall surface areas that must be cooled and also increase the physical envelope that must be accommodated. More data are needed regarding the effect of CR on autoignition at high H_2O_2 concentrations, specifically at CRs less than 6.

This paper presents results from an investigation of the effects of hydrogen peroxide concentration (85–98% by weight), chamber CR (3 and 5), and equivalence ratio (1.4–2.8) on the autoignition of JP-8 fuel in decomposed H_2O_2. The fluid mechanics of transverse injectors are discussed as well as the basics of autoignition. A summary of past data concerning the autoignition of kerosene fuel in air and decomposed hydrogen peroxide is presented, and a flame stability model is outlined for a dump combustor. Finally, an autoignition experiment and analysis procedure is described and results are given.

Each test outcome could be broken down into three regimes: strong, weak, and no autoignition. Those tests classified in the weak-autoignition regime contained significant chamber pressure oscillations with dominant frequencies between 27 and 47 Hz. Results showed that as hydrogen peroxide concentration and/or CR were increased the equivalence ratio defining the autoignition boundary increased as well in agreement with past kerosene autoignition data.

Approach

The staged combustor used during autoignition testing was originally designed for use in a rocket-based combined cycle application.[9] To expand the operating range of the combustor in terms of H_2O_2 concentration two catalyst beds were used. These were designated catalyst bed 1 (CB-1), which was used in the original combustor design, and catalyst bed 2 (CB-2). The design operating parameters of each bed are summarized in Table 2. Because the catalyst beds have different exit geometries, two different combustor assemblies were used during the course of autoignition testing. A schematic of each combustor assembly, indicating the positions of pressure transducers and thermocouples, is shown in Fig. 1. Each assembly was composed of a catalyst bed, mating hardware, transverse injector assembly, fuel film injector assembly (fuel film cooling was not used during autoignition testing), combustion chamber, and nozzle. A modular throat allowed for variation in chamber contraction ratio.

Four grounded type-K thermocouples, made by Omega Engineering, Inc., were used in the combustion chamber to withstand the high temperatures present there. The probe of each thermocouple was encased in a stainless steel sheath that allows operation up to 1255 K (1800°F). These probes were positioned flush with the inner chamber wall and spaced equally along the length of the chamber to measure the temperature profile in the combustor. Immediately downstream of each catalyst bed an exposed thermocouple was positioned such that the probe was at the centerline of the duct. This thermocouple was used to measure the hydrogen peroxide decomposition temperature. Three Druck pressure transducers [20.7 MPa (3000 psia) max ± 0.05 MPa (± 7.5 psia) accuracy] were used in each engine assembly. The transducer at the first axial position in the chamber section measured the conditions in the recirculation zone behind the rearward-facing step. This step will be discussed in further detail in the next section. A thermocouple was also surface-welded to the outer wall of CB-1 to monitor its temperature.

The combustion chamber and nozzle were made of copper because of its high thermal diffusivity. The chamber had an inner diameter of 6.5 cm (2.56 in.) and was 19.6 cm (7.7 in.) in length from the edge of the rearward-facing step to the beginning of the nozzle contraction. Three nozzles were available at CRs of 3.0, 5.0, and 6.5 setting the L^* at 61, 102, and 135 cm (24, 40, and 53 in.), respectively. Characteristic length L^* is defined as the ratio of the chamber internal volume, from the edge of the rearward-facing step to the plane of the nozzle throat, to the nozzle throat cross-sectional area. All injector hardware including the rearward-facing step was fabricated from stainless steel (SS 304). Viton O-rings were used to seal most of the interfaces between combustor hardware. This material is compatible with hydrogen peroxide and has a maximum operating temperature of 480 K (400°F). Pressure-filled stainless steel O-rings were used for sealing between the catalyst beds and their mating pieces. These O-rings were specified by the catalyst bed manufacturers.

Injector Design

A typical transverse, or crossflow, injector was used in this study and is shown schematically in Figs. 1 and 2. In this setup multiple jets of liquid (kerosene fuel in this case) are injected normal to the high-temperature, subsonic, decomposed hydrogen peroxide flow. Drag forces are exerted on the liquid jet by the gas, deflecting the liquid and changing its trajectory. A rearward step (increase in chamber diameter) is found downstream of the fuel injection point. The transverse injector was chosen for this study because it is well understood from the design standpoint. Correlations can be employed to create trajectory predictions, and orifice design requires little computational effort. Good atomization can also be achieved with the injector, but flame holding becomes an important issue due to the high gas velocity. To overcome this, bluff-body flame stabilization is often used, such as a rearward step in this particular design. In high-temperature combustors, fuel film wall cooling is commonly used in tandem with this injector to keep wall temperatures low.[9] This also adds complexity to the combustor design and in some cases will react with the core flow.[6] Fuel film cooling was neither used nor required in this study because the tests were limited to approximately 1 s in duration. A detailed discussion on the transverse injector design used in this study can be found in Refs. 10 and 11. The focus of this paper is on the influence of flame stabilization and fuel-jet trajectory on autoignition.

Flame Holding

To enhance the performance of the combustor used in this study a rearward-facing step was included in the design to provide flame

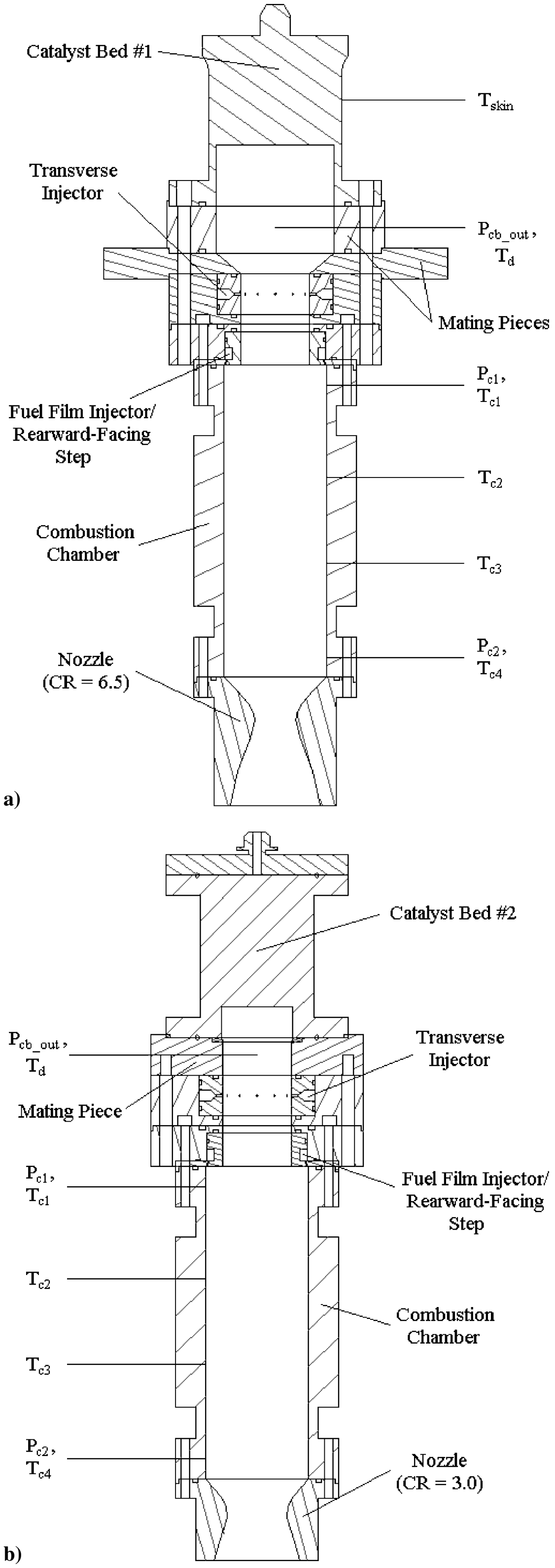

Fig. 1 Comparison of combustor assemblies using a) CB-1 and b) CB-2; axial locations of instrumentation are indicated in schematic.

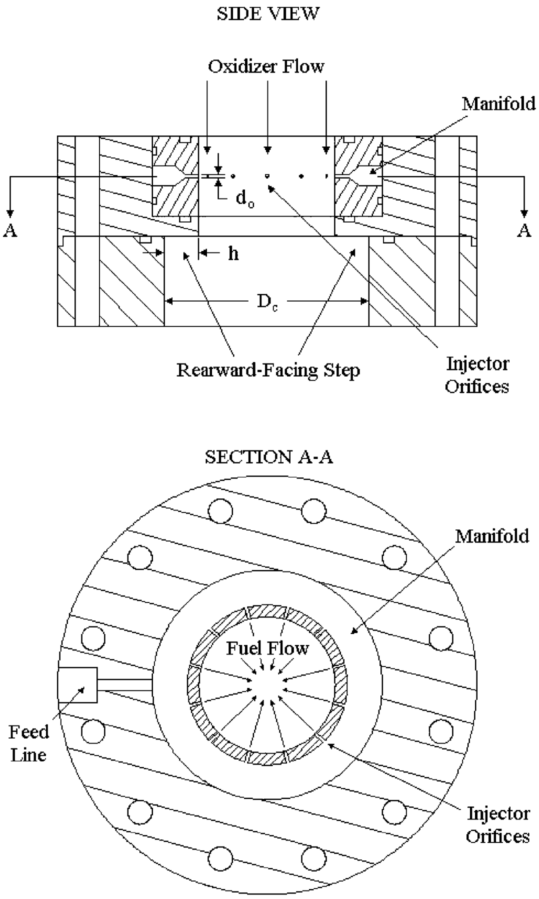

Fig. 2 Schematic of transverse injector in a dump-combustor configuration.

holding downstream of the transverse injector. This type of configuration is commonly referred to as a dump combustor. The rearward-facing step plays an important role in not only anchoring the flame but also in autoignition. A turbulent shear layer is created between the freestream flow and the recirculating flow behind the step. This shear layer contains large-scale turbulent eddies, and if given sufficient time to do so the propellant mixture contained in these hot eddies can autoignite.[12] Once autoignition has taken place the recirculating combustion products feed the incoming mixture of fuel vapor and decomposed gases to sustain the reaction and anchor the flame.

The rearward-facing step used in this study was sized to maximize the turbulent mixing time, which is usually taken to be equal to the characteristic breakdown time of the eddies.[12] Knowledge of the characteristic length scale of the turbulent eddies is required to determine the breakdown time, and experimental results have shown that this length scale is equal to the width of the flameholder.[12] For this step configuration, the flameholder width is equal to twice the height of the rearward-facing step. The shear layer characteristic time can then be written as

$$\tau_{\text{sl}} = 2h/V_g \tag{1}$$

From continuity the gas velocity at the edge of the rearward-facing step is dependent on mass flow rate, density, and flow area. Because flow area can be expressed in terms of the chamber diameter D_c and h, an expression can be derived from Eq. (1) for the optimum step height assuming constant mass flow and density[12,13]:

$$h_{\text{opt}} = D_c/6 \tag{2}$$

The combustor used in this study contained a rearward-facing step sized according to Eq. (2). The step height and chamber diameter remained fixed throughout autoignition testing.

Jet Trajectory

In a staged-bipropellant dump combustor, shear-layer flow and fuel vaporization have a significant effect on the trajectory of the ligaments and droplets that form following the breakup of a liquid jet. Many empirical trajectory models have been formulated to predict the bulk trajectory of a liquid jet as far as 100 or more x/d_o downstream of the injection point.[14] However, under the flow and heat transfer conditions present in this combustor, the correlations will only be accurate in predicting the trajectory before column breakup. For this reason, an empirical correlation developed by Wu et al.[15] was used in this study to analyze the effect of jet trajectory on autoignition. This correlation was developed based on observations of the trajectory of a liquid column before its column fracture point: $x/d_o < 10$. The trajectory for a kerosene jet in crossflow, derived from Wu et al., is stated as follows:

$$y/d_o = 1.35\sqrt{Q(x/d_o)} \tag{3}$$

It is important to note that the jet trajectory is primarily dependent on the liquid-to-gas momentum ratio. The higher the momentum ratio the greater the jet will penetrate into the gas stream at a specific axial location. The momentum for each flow is defined as density multiplied by the square of the velocity. Substituting the continuity equation solved for velocity and the ideal gas equation solved for density into this definition of momentum, it is found to be dependent on mass flow rate, cross-sectional area, temperature, and pressure. For a constant mass flow rate, cross-sectional area, and decomposition temperature, the momentum of the decomposed gas is only a function of pressure. The significance of this will become apparent later in this paper.

Wu et al. also determined that the axial breakup position of a transverse jet in crossflow is always at an x/d_o of approximately 8. This relation was used to aid in the design of the injector specifically with respect to the distance between the injector orifices and the rearward-facing step. Preferably, one would like to have a fully premixed fuel and oxidizer stream prior to reaching the edge of the rearward-facing step to increase the likelihood of autoignition in the shear-layer eddies. At the very least, one would prefer to have a well-atomized liquid jet upstream of the step. For this reason the rearward-facing step was placed well downstream (x/d_o of approximately 50) of the axial breakup point predicted by the Wu et al. relation.

This relation was also used to determine the penetration of the fuel jet at the point of jet breakup in this study. If the jet penetration is too shallow (low momentum ratio), the liquid will not be dispersed well within the chamber and will tend to hug tightly to the chamber wall, causing a fuel-rich periphery and an oxidizer-rich core. If the penetration is too deep (high momentum ratio), the streams will collide and coalesce at the centerline of the chamber, resulting in a fuel-rich core and possibly poor vaporization. Both cases result in poor dispersion of the liquid within the chamber and could affect autoignition.

In this study a fixed-geometry injector was used in the combustor to avoid having to frequently switch out injector hardware. This necessitated the use of a constant fuel mass flow rate to maintain a reasonable orifice exit velocity and injector pressure drop at all tested conditions. Large deviations from the design mass flow rate would have resulted in poor injector performance and limited operational flexibility. As a result, equivalence ratio was varied through modifications in the mass flow rate of hydrogen peroxide. This method of modifying the overall equivalence ratio also results in variations in fuel-jet trajectory, atomization, and local quantity of vaporized fuel (or local ϕ) at each tested condition. Modifications to the chamber CR caused similar effects.

Autoignition

Autoignition, also known as spontaneous or thermal ignition, is the initiation of a self-sustained exothermic (combustion) reaction without the aid of an external energy source. The reactants themselves have enough energy to start and continue the reaction. The exact process leading to autoignition is not completely understood, but it is known to be dominated by a combination of chemical kinetic and fluid dynamic processes. Kerosene-based fuels such as JP-8 contain a number of different hydrocarbons including aromatics, naphthenes, paraffins, and olefins.[16,17] The average molecular formula of JP-8 is $C_{11}H_{21}$.[17] The autoignition of high-molecular-weight hydrocarbons is a complicated, multistep process. In a reacting flow, ignition is usually defined to occur at the point when a flame is visible in the flow.

The time required to complete each reaction in the combustion process is dictated by chemical kinetics. According to the Arrhenius relation, the rate constant of any reaction is inversely proportional to the exponential function of the inverse of the mixture temperature. The reaction rate is proportional to the reaction rate constant, and so as the temperature increases the reaction rate increases. Many past studies of kerosene autoignition attempted to couple the fluid mechanics of a reacting flow of fuel and oxidizer with chemical kinetics using the Arrhenius relation. This was done by equating the reaction time, expressed as a modified form of the Arrhenius relation, to the residence time of the gaseous mixture. The following sections will attempt to summarize past work on autoignition of kerosene in air and in decomposed hydrogen peroxide. Also, a model used to describe flame stability behind a rearward-facing step will be outlined.

Kerosene Autoignition in Air

Since the 1970s there has been significant research conducted on the autoignition behavior of kerosene fuel in air. Many of these studies were performed initially to simulate conditions in lean, premixed gas-turbine engine combustors.[18–21] Experimental research was aimed at developing correlations and models for predicting ignition delay based on operating conditions.

Many of these autoignition studies used a continuous-flow apparatus. The setup usually consisted of a tube or duct through which heated air flows at high subsonic velocity. The fuel is injected into the airstream where it mixes and reacts. The method of injection is extremely important, especially for liquid fuels, in minimizing effects of vaporization on ignition delay and for obtaining a uniform mixture of fuel and air. Ignition is verified through the direct visual observation of a flame inside the duct (for windowed setups) or exiting the chamber. Ignition delay is calculated using the air velocity and the distance from the injection point to the position of the visible flame.

Ignition delay correlations from these studies are derived from chemical kinetics and make use of the Arrhenius relation. The reaction is treated as a whole using the global activation energy determined from experimental data. Correlations for ignition delay of hydrocarbons in air usually take the following form[18]:

$$\tau_i = B\exp(E_a/R_uT)[\mathrm{Fuel}]^j[\mathrm{O}_2]^m p^n \tag{4}$$

where [Fuel] and $[O_2]$ are the concentrations of gaseous fuel and oxygen, respectively. The parameter B and exponents j, m, and n are empirically determined constants. Values of the constants in Eq. (4) vary from experiment to experiment for a particular fuel, but the trends are generally similar.[18]

There have been a number of autoignition studies with kerosene-based fuel and air in a continuous-flow apparatus. Spadaccini and TeVelde[19] studied Jet-A fuel at equivalence ratios ranging from 0.3 to 0.7, temperatures from 700 to 1000 K (800 to 1350°F), pressures from 1.0 to 3.1 MPa (150 to 450 psia), and air velocities from 20 to 100 m/s (65 to 330 ft/s). Results indicated that equivalence ratio did not affect ignition delay. In addition, ignition delay (or, more appropriately, residence time required for autoignition) was shown to be inversely proportional to the square of the air static pressure. Spadaccini and TeVelde chose to correlate their results using a form of Eq. (4). They noted that most ignition delay correlations are fitted with a pressure exponent of unity ($n = -1.0$), but their data suggested that an exponent of -2.0 is a better fit especially at high temperatures. The effect of fuel concentration distribution was also investigated in this study and was found to influence the ignition delay for short residence times. However, as the residence time was increased the effect became negligible.

A study by Freeman and Lefebvre[18,20] was also performed with Jet-A, but at atmospheric pressure. Tests were conducted at equivalence ratios from 0.2 to 0.8, velocities from 10 to 40 m/s (30 to 130 ft/s), and temperatures up to 1060 K (1450°F). Freeman and Lefebvre found that the equivalence ratio had a negligible effect on ignition delay for $\phi < 1.0$, in agreement with Spadaccini and TeVelde, and chose to correlate their data according to Eq. (4) as well. Increasing the oxygen concentration of the incoming air was found to decrease the ignition delay and Freeman and Lefebvre set the exponent m, from Eq. (4), equal to -0.65 based on experimental data. The fuel temperature was also found to have negligible effect on ignition delay, consistent with Spadaccini and TeVelde's results.

Mestre and Ducourneau[21] performed autoignition testing of kerosene fuel over a wide range of equivalence ratios from approximately 0.8 to 8.0, pressures from 0.55 to 1.1 MPa (80 to 160 psia), an average air velocity of 65 m/s (215 ft/s), and temperatures up to 1090 K (1500°F). Their experimental results showed that the autoignition temperature plotted as a function of equivalence ratio at a constant pressure had a minimum that varied with pressure. This minimum temperature moved from an equivalence ratio of almost 3.0 at 0.55 MPa (80 psia) to approximately 1.0 at 1.1 MPa (160 psia). Data also showed that the required autoignition temperature decreased with increasing pressure, but the decrease became smaller as pressure neared approximately 1.0 MPa (145 psia). The study also found that the required autoignition temperature decreased with increasing residence time at constant ϕ. They did not correlate their results according to Eq. (4).

In general, there is good agreement among each of the studies discussed in that as temperature and/or pressure are increased the likelihood of autoignition also increases, assuming a constant residence time and ϕ. Also, these studies agree that as residence time is increased the temperature required for autoignition decreases at constant pressure and ϕ. However, there is some differing data regarding the effect of equivalence ratio on autoignition. Two of the studies noted a negligible effect due to changes in equivalence ratio, for $\phi < 1.0$, at similar temperature, pressure, and residence time. However, Mestre and Ducourneau observed that equivalence ratio had a significant effect on autoignition temperature with residence time and pressure held constant.

Dump-Combustor Flame Stability

For a stable flame to exist in a dump combustor the rearward-facing step must provide sufficient shear-layer residence time or the flame will blow off. A study by Plee and Mellor[12] outlined the development of a model to predict blowoff for various flameholder geometries under fuel-lean conditions. For a fuel-lean, premixed flow the relation can be stated as follows[12]:

$$\tau_{\mathrm{sl}} = m\tau_i + b \tag{5}$$

The slope and intercept of the equation for the blowoff limit were determined empirically. Plee and Mellor suggested the use of the following relation for ignition delay for fuel-lean equivalence ratios:

$$\tau_i = K(T_{\mathrm{af}}/T_{\mathrm{in}})\exp(E_a/R_u T)(1/\phi) \tag{6}$$

where K is an empirical constant. The model defines a boundary for blowoff in terms of shear-layer characteristic time. If the shear-layer residence time, calculated using Eq. (1), is greater than the value determined by Eq. (5), the models predicts that a stable flame will exist behind the rearward-facing step. The model predicts flame blowoff if the residence time calculated from Eq. (1) is less than that found from Eq. (5). Although this model was developed for premixed flames, which are not present in this study, the model was considered in correlating autoignition data due to its simplicity.

Data from Mestre and Ducourneau showed that autoignition temperature increases with increasing equivalence ratio for fuel-rich mixture ratios. This suggests that the ignition delay increases with equivalence ratio for fuel-rich mixtures. Equation (6) would show the opposite trend if used for fuel-rich conditions and, therefore, should be restricted only to fuel-lean equivalence ratios. Note that this relation for ignition delay does not include a pressure term.

Kerosene Autoignition in Staged Combustors

Research into the autoignition characteristics of kerosene fuel in decomposed hydrogen peroxide has not been as substantial as it has been in air. Much of the data concerning autoignition in staged engines is the result of problems encountered during engine design. However, there was a series of papers written in the early 1950s on autoignition of kerosene fuel in decomposed hydrogen peroxide by Walder,[22,23] Walder and Purchase,[24] and Walder and Broughton.[2]

The most extensive of these autoignition studies by Walder is found in his earliest paper.[22] In this study 80% H_2O_2 was decomposed in a catalyst stone bed giving a decomposition temperature of approximately 780 K (950°F). Tests to determine autoignition temperature were conducted similarly to those done with kerosene in air. Initially water was mixed with the liquid hydrogen peroxide to drop the decomposition temperature below 670 K (750°F). The water flow was gradually reduced to increase the decomposed gas temperature until autoignition was verified by visual detection of a flame exiting the chamber throat. Aviation kerosene fuel was fed to the chamber through 12 swirl injectors and the residence time of the gas in the chamber was modified by varying the chamber length and throat diameter. The CR was varied from approximately 6.5 to 20. All tests were conducted at a mixture ratio of 9.1, which is approximately stoichiometric for 80% H_2O_2.

Walder developed a correlation for the autoignition temperature of kerosene in decomposed hydrogen peroxide similar in form to Eq. (4). The main difference was that Walder supposed that the ignition delay was proportional to L^* of the engine. The basic form of the correlation is as follows:

$$\log(L^* p^n) = K/T_d + L \tag{7}$$

where K, L, and n are empirical constants. The slope of a line describing autoignition pressure vs characteristic length at constant temperature gives the value of the exponent n. Walder found n to be equal to 1.15 based on test data. This value is close to unity, which Spadaccini and TeVelde suggested worked well for autoignition of kerosene in air at low temperatures. The constants K and L are the slope and intercept of a line plotting autoignition temperature as a function of L^* at constant pressure. Walder found these constants to be equal to 3720 and -2.62, respectively, based on test data. From this relation one can see that as L^* and/or chamber pressure are increased the temperature required for autoignition decreases. This agrees with the results from Mestre and Ducourneau. Walder also investigated the effect of equivalence ratio on the autoignition temperature at constant pressure of 0.70 MPa (100 psia) and L^* of 128 cm (50.4 in.). It was found that the required autoignition temperature rose to a value of about 716 K (830°F) at an equivalence ratio of 1.25 from 702 K (805°F) at the stoichiometric value. At an equivalence ratio of approximately 0.8 the required autoignition temperature fell to 683 K (770°F). The trend in these results also agrees with that of Mestre and Ducourneau for fuel-rich equivalence ratios.

Another study, by Walder and Purchase,[24] investigated the affect of injector design on autoignition temperature. A number of complex injector designs were tested that made use of swirl jet, straight orifice, and combined swirl and straight orifice injection techniques. All tests were conducted at a stoichiometric mixture ratio of 9.1 for 80% H_2O_2 and L^* ranging from 173 to 254 cm (68 to 100 in.). The average autoignition temperature was found to vary with injector design, which suggests that autoignition is dependent on the atomization and vaporization processes that control local mixing as well as the global parameters of ϕ and T.

A study by Wu et al.[6] on the development of staged-bipropellant combustors using hydrogen peroxide and JP-8 noted some problems obtaining autoignition. The test combustor was very similar in design to that presented in this paper. A silver screen catalyst bed was used to decompose 85% H_2O_2 at 95% efficiency and the combustor used a transverse-type injector design with a rearward step. Autoignition was not achieved at a monopropellant operation chamber pressure of 2.3 MPa (340 psia) and a CR of 5.4. The mixture ratio used during this test is unclear but other data from the study suggest that it was somewhere between 6.0 and 11.0, corresponding to equivalence ratios between 0.8 and 1.4. The CR was increased to 7.11 to establish reliable autoignition.

In a study by Coxhill et al.,[25] autoignition problems were also experienced during staged engine development. This combustor design used kerosene fuel jet injectors angled at 55 deg to the decomposed gas flow and did not incorporate flame-holding geometry. A silver screen catalyst bed was used to decompose 90% H_2O_2 and the combustor operated at mixture ratios from 6.0 to 10.0, or equivalence ratios from 0.8 to 1.3. Autoignition did not occur at a CR of approximately 13.0 at chamber pressures less than 1.1 MPa (160 psia) even for fully decomposed hydrogen peroxide. At a CR of about 20.0, autoignition was achieved for all tested conditions and was subsequently used in the final combustor design.

Past data suggest autoignition is influenced by temperature, pressure, and equivalence ratio, especially at fuel-rich conditions. Also, CR, or chamber residence time, has been shown to be extremely important to autoignition. The experiment described here adds to the body of literature, seeking to establish autoignition limits for JP-8 under varying CR, equivalence ratio, and hydrogen peroxide concentration. The temperature of the decomposed gases is controlled by the H_2O_2 concentration and the residence time is controlled by the chamber CR. Tests are conducted at lower CRs (3.0 and 5.0), higher equivalence ratios (1.4–2.8), higher temperatures (900–1225 K or 1173–1746°F), and higher oxygen concentrations (O_2 mass fractions of 0.40–0.46) than previous kerosene autoignition studies.

Results

Test Classifications

A total of 24 tests were conducted to investigate the relative affects of equivalence ratio, decomposed gas temperature, and CR on the autoignition of JP-8 in decomposed hydrogen peroxide. Hydrogen peroxide concentration was varied from 85 to 98%, equivalence ratios ranged from 1.4 to 4.0, and CR was set to values of 3.0, 5.0, and 6.5. Autoignition was classified into three regimes: strong, weak, and no ignition based on visual observations from video and recorded chamber pressure data.

Each autoignition test followed an identical timing sequence. At $t = 0$ s, the hydrogen peroxide flow was initiated and introduced into the catalyst bed. One half-second later the JP-8 flow was supplied to the transverse injector. During this 0.5-s period of hydrogen peroxide flow only, the monopropellant chamber pressure was established in the combustor. The JP-8 flow was sustained for a full second, which was more than sufficient in duration to obtain autoignition if the conditions were correct. Once the fuel flow was ceased it was followed by 1–2 s of hydrogen peroxide–only flow. This lag of hydrogen peroxide was used to vaporize or burn off any remaining fuel in the combustor.

Tests that resulted in strong autoignition were characterized by bright, stable red-orange flames and calculated bipropellant C^* efficiencies of over 90%. The delay between the initiation of fuel injection and autoignition was typically small, less than 50 ms. As Fig. 3, shows, the chamber pressure, p_{c2}, rises sharply from its monopropellant level, indicating autoignition, approximately 0.1 s following the rise in the fuel-injector pressure, $p_{\mathrm{fu\_inj}}$. This delay most likely corresponds to the time required to fill the fuel manifold as the pressure drop across the injector reaches approximately 0.70 MPa (100 psi), which was the design pressure drop, at this instant as well. The chamber pressure for a strong autoignition test typically increases by approximately 100% from monopropellant to bipropellant modes. This was due to the added mass of fuel in the chamber and the energy released by the combustion reaction. For this particular test the monopropellant decomposition efficiency was approximately 97% whereas the bipropellant C^* efficiency was about 94%. The pressure profiles for strong autoignition tests were similar for both catalyst beds.

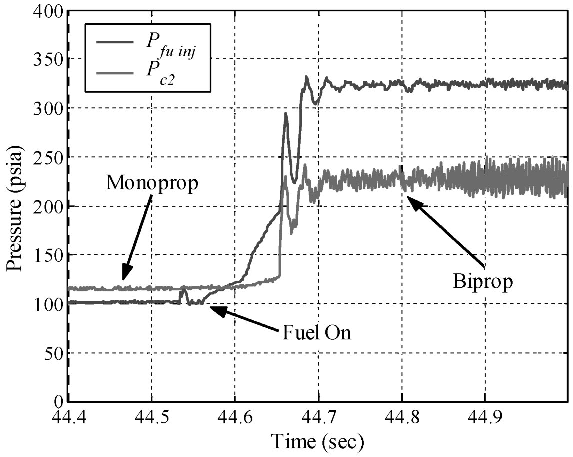

Fig. 3 Plot of $p_{\mathrm{fu\_inj}}$ and p_{c2} at the point of injection for a strong autoignition test using CB-1 (test conditions: 90% H_2O_2, $\phi = 1.59$, and CR = 3.0).

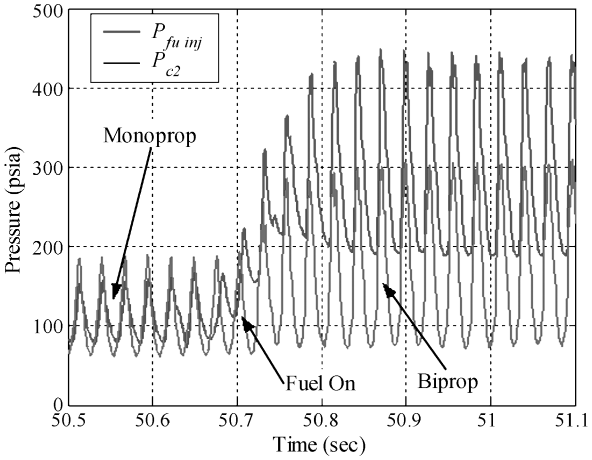

Fig. 4 Plot of $p_{\mathrm{fu\_inj}}$ and p_{c2} at the point of injection for a weak-autoignition test using CB-1 (test conditions: 87.5% H_2O_2, $\phi = 1.62$, and CR = 3.0).

Tests classified as resulting in weak autoignition typically produced flames that were very unstable and varied in color and intensity. These tests were characterized by large chamber pressure instabilities, in most cases, and resulted in bipropellant C^* efficiencies ranging from 60 to 90%. A typical plot of fuel-injector and chamber pressure at the start of the bipropellant portion of a weak autoignition test is shown in Fig. 4. As the plot shows, the chamber pressure data for this test contained significant pressure oscillations, the amplitude of which is nearly equivalent to the average chamber pressure. The monopropellant decomposition efficiency for this test was about 93% and the bipropellant C^* efficiency was approximately 69%. Following fuel injection, pressure instability with a dominant frequency between 27 and 47 Hz was measured during all weak-autoignition tests. In most cases, the amplitude of the oscillation was greater than 10% of the average chamber pressure. It is believed that the pressure oscillations were primarily a result of the behavior of CB-1, because these disturbances were only observed during the operation of that particular bed. Also, in most cases, the pressure oscillations were present during monopropellant operation of the combustor before the fuel was introduced to the chamber, albeit at lower amplitude.

During tests in which no autoignition occurred, a thick cloud of vapor was typically seen issuing from the nozzle following fuel injection. In some cases, the difference in appearance between the exhaust during monopropellant mode and following fuel injection was almost unnoticeable. In general, flames were not seen exiting the engine during tests classified as no ignition. However, sparks of flame were sometimes seen at shutdown. A plot of fuel-injector inlet pressure and chamber pressure for a no-autoignition test is shown in Fig. 5. Following fuel injection the chamber pressure rises by only about 0.07 MPa (10 psi) or 6% of the monopropellant chamber pressure. This small increase in pressure is a result of the fuel being vaporized in the chamber. A sharp increase in pressure does not occur following fuel injection as it does in the strong- and weak-autoignition cases, which suggests that the decomposed gas had only enough energy to vaporize the fuel and not enough to ignite the resulting mixture. The monopropellant decomposition efficiency for this test was approximately 82% whereas the bipropellant C* efficiency was about 47%. Bipropellant C* efficiencies for all no-ignition cases were less than 65%.

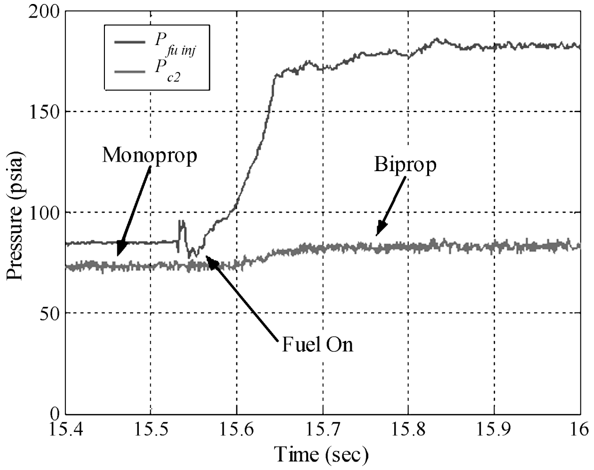

Fig. 5 Plot of $p_{\mathrm{fu\_inj}}$ and p_{c2} at the point of injection for a no-autoignition test using CB-2 (test conditions: 94% H_2O_2, $\phi = 2.15$, and CR = 3.0).

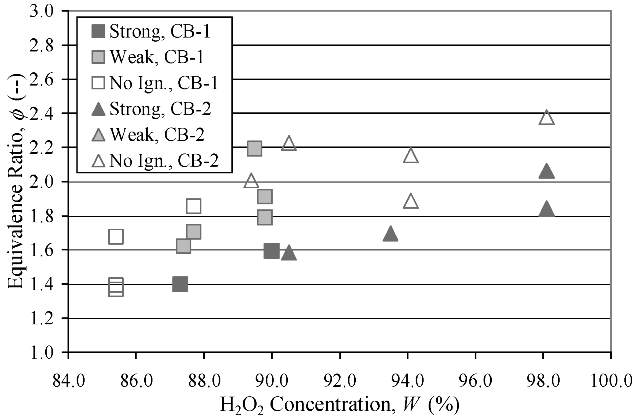

Fig. 6 Autoignition of JP-8 as a function of ϕ and H_2O_2 concentration at CR = 3.0.

Effect of H_2O_2 Concentration

One of the goals of this study was to determine the effect of equivalence ratio and decomposition temperature on autoignition of JP-8. A total of 20 tests were conducted at a CR of 3.0 to determine the autoignition boundary in terms of equivalence ratio at a constant H_2O_2 concentration. Hydrogen peroxide concentrations of 85, 87.5, 90, 94, and 98% were used to vary the decomposition gas temperature. CB-1 was used for concentrations of 90% and below whereas CB-2 was used for concentrations 90% and above. The data resulting from these tests are shown in Fig. 6.

As Fig. 6 shows, the strong autoignition boundary in terms of equivalence ratio widens with increasing hydrogen peroxide concentration. It stretches from a value of, presumably, less than 1.37 at a concentration of 85% to 2.06 at a concentration of 98%. However, the autoignition boundary is not necessarily clearly defined, especially at concentrations of 85, 87.5, and 90%. At a concentration of 85% a strong- or weak-autoignition condition was not found even at an equivalence ratio as low as 1.37. A test was not conducted at a lower equivalence ratio because the oxidizer flow rate needed to reach a ϕ of 1.37 was close to the highest recommended flow rate for CB-1. At concentrations of 87.5 and 90% weak autoignition was observed over a wide range of equivalence ratios before reaching a no-autoignition condition. For instance, at 90% H_2O_2, strong autoignition was observed at the baseline equivalence ratio of 1.59 using CB-1. However, a no-autoignition condition was not found until the equivalence ratio was raised to 2.19. Similarly, at a concentration of 87.5% using CB-1, strong autoignition was observed at an equivalence ratio of 1.40, but a no-autoignition condition was not achieved until ϕ was raised to 1.86. At concentrations of 94 and 98% strong autoignition was observed at equivalence ratios of 1.70 and 2.06, respectively, with CB-2.

Table 3 Variation in decomposition temperature and oxygen mass fraction with H_2O_2 concentration

W, %	Decomposition temperature, K (°F)	O_2 mass fraction	Stoichiometric O/F mass ratio
85.0	907 (1173)	0.400	8.49
87.5	968 (1283)	0.412	8.25
90.0	1029 (1393)	0.423	8.02
94.0	1128 (1570)	0.442	7.68
98.0	1225 (1746)	0.461	7.36

CB-2 was tested at three test conditions that were nearly identical to those run with CB-1. At the baseline conditions, 90% H_2O_2 and ϕ of 1.60, CB-2 produced a strong autoignition result in agreement with that of CB-1. Running CB-2 at equivalence ratios of 2.01 and 2.23 resulted in no autoignition rather than weak autoignition like CB-1 produced at ϕ of 1.91 and 2.19. In fact, CB-2 did not produce weak-autoignition results at any of the tested conditions. The authors believe that the pressure oscillations observed during the weak-autoignition tests were a function of the catalyst bed, CB-1, for this reason. It is also believed that these pressure oscillations effectively pushed the propellant mixture back and forth across the autoignition boundary, resulting in the fluctuating flame structure observed during weak-autoignition tests. This suggests that chamber pressure plays a very important role in defining the conditions necessary for autoignition, which agrees with past autoignition studies.

The primary reason for the increase in autoignition limits with H_2O_2 concentration is the corresponding increase in the decomposition temperature. Assuming 100% decomposition efficiency the gas temperature increases by 318 K (573°F) from a concentration of 85–98% H_2O_2, as shown in Table 3. This result agrees well with the results of Mestre and Ducourneau[21] as well as Walder,[22] who both showed that fuel-rich autoignition limits increase with increasing temperature at constant pressure for kerosene in air and decomposed hydrogen peroxide, respectively. Spadaccini and TeVelde[19] as well as Freeman and Lefebvre[20] chose to correlate their data on kerosene in air at fuel-lean equivalence ratios using a form of Eq. (4) that shows that ignition delay is exponentially dependent on temperature. As a result of this exponential dependence, temperature has by far the most dominant effect on ignition delay according to Eq. (4). Applying this to the present study, a change in H_2O_2 concentration from 85 to 90% would increase the decomposition temperature by 122 K (220°F), significantly decreasing the ignition delay. The shorter the ignition delay the greater is the chance of achieving autoignition within the combustion chamber.

Coupled to this temperature effect is the increasing mass fraction of oxygen present in the decomposed gases as concentration increases, as Table 3 shows. This increase may also contribute to the increased autoignition limits at high concentrations, in agreement with the results of Freeman and Lefebvre.[20] However, oxygen concentration was not measured in this study and so its effect on autoignition cannot be shown conclusively.

Effect of Contraction Ratio

Another goal of this study was to determine the effect of gas velocity, or residence time, on the autoignition of JP-8 in decomposed peroxide. For a dump combustor there are two residence times that must be considered: the chamber residence time and the shear-layer residence time. Chamber residence time is varied through changes in the chamber CR, which alters the chamber Mach number and gas velocity. The CR was altered in this study by modifying the chamber throat diameter. For this combustor the height of the rearward step was kept fixed, which meant that the primary means of varying the shear-layer residence time was through the gas velocity at the step. Theoretically, changes in CR should not have a significant effect on this velocity. However, because the throat diameter was modified to change CR in this study while mass flow rates were kept fixed,

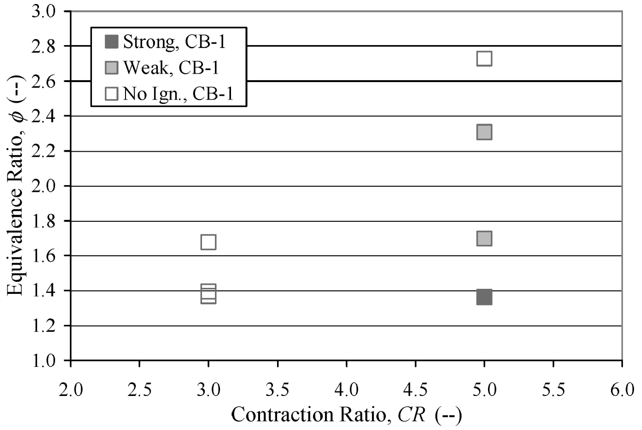

Fig. 7 Autoignition of JP-8 as a function of equivalence ratio and CR at a constant H_2O_2 concentration of 85%.

the chamber pressure was consequently altered, adjusting the gas velocity at the step in the process. As a result, the effects of chamber and shear-layer residence time were unavoidably coupled through CR in this investigation.

Four additional tests were performed at a CR of 5.0 and a constant concentration of 85% using CB-1 to determine the autoignition boundary in terms of equivalence ratio. The data resulting from these tests along with those done at a CR of 3.0 with 85% H_2O_2 are shown in Fig. 7. Strong autoignition was achieved at an equivalence ratio of 1.36 at a CR of 5.0, but no autoignition was achieved with a CR of 3.0 at the same equivalence ratio. The equivalence ratio was increased from 1.36 at a CR of 5.0 in an attempt to find a no-autoignition point. Weak autoignition was observed at equivalence ratios of 1.70 and 2.31, and a no-autoignition point was found at a ϕ of 2.73.

Although strong autoignition was not achieved at a CR of 3.0, these results indicate a broadening of the autoignition limits with increasing CR. This is a direct result of the increase in both the chamber and shear-layer residence times with CR. At a CR of 3.0 the chamber residence time was calculated to be approximately 2.2 ms, whereas the shear-layer residence time was calculated to be on the order of 0.08 ms. When the CR was increased to 5.0 the chamber residence time increased to about 3.7 ms whereas the shear-layer time was around 0.13 ms. All residence times were calculated assuming a stream of decomposed 85% H_2O_2 alone, ignoring fuel vapor effects. The increase in each residence time between a CR of 3.0 and 5.0 was calculated to be approximately 65%. As a result, it is unclear which residence time, chamber or shear layer, had the most significant effect on broadening the autoignition limits at a CR of 5.0. The general trend in this data agrees with the studies of Mestre and Ducourneau[21] as well as that of Walder,[22] who found that the likelihood for autoignition at constant temperature, pressure, and equivalence ratio increases with increasing residence time.

Pressure Effect

During the investigation into the effect of equivalence ratio on autoignition at constant CR, the equivalence ratio was increased by decreasing the flow rate of hydrogen peroxide with the fuel flow rate held constant. This resulted in a decrease in monopropellant chamber pressure before fuel injection, coupling the effects of increasing equivalence ratio and decreasing chamber pressure on autoignition. For instance, when running with 94% H_2O_2 at a ϕ of 1.70 and a CR of 3.0, the monopropellant chamber pressure was measured at approximately 0.65 MPa (94 psia), but when ϕ was increased to 2.15 the pressure dropped to about 0.50 MPa (72 psia). Similarly, when exploring the effect of CR on autoignition, both the H_2O_2 and JP-8 flow rates were held constant while the throat diameter was varied. As the CR was increased, throat diameter decreased; it consequently resulted in an increase in the monopropellant chamber pressure. For example, at a constant ϕ of 1.36 with 85% H_2O_2, the monopropellant chamber pressure was about 0.70 MPa (100 psia) at a CR of 3.0 but increased to approximately 1.30 MPa (190 psia) at a CR of 5.0. Therefore, the effect of increasing CR was coupled to that of increasing chamber pressure.

Nearly all of the past kerosene autoignition studies reviewed in this paper have included a pressure effect in their autoignition correlations.[19,21,22] The extent of the influence of pressure has not been agreed upon; however, the general trend suggests that increasing pressure broadens autoignition limits. In this study, pressure effects were coupled with changes in both equivalence ratio and CR. Therefore, it cannot be conclusively stated that ϕ and CR were solely responsible for the trends observed in the data. It is believed that the pressure oscillations observed during weak-autoignition tests pushed the propellant mixture back and forth across the autoignition boundary. This illustrates the importance of the effect of pressure on autoignition.

Trajectory Effect

The liquid jet trajectory correlation developed by Wu et al.,[15] described previously, was used to estimate the fuel trajectory based on tested conditions. Again, this correlation was developed to predict a jet's trajectory before column breakup and is inaccurate farther downstream. Breakup was assumed to occur at an x/d_o of 8, according to Wu et al. The goal of this analysis was to understand the potential influence of fuel distribution on autoignition. Multiple-jet interaction was not considered in this analysis; rather the calculations were performed for a single fuel jet. According to the Wu et al. correlation, the jet trajectory is dependent on the liquid-to-gas momentum ratio, where momentum is defined as density times the square of velocity. Because the fuel flow rate and injector geometry were kept fixed during this study, so too was the fuel momentum. Therefore, only the variations in the momentum of the decomposed H_2O_2 gas affected the jet trajectory. As discussed previously, gas momentum is dependent on mass flow rate, cross-sectional area, temperature, and pressure. The cross-sectional area of the gas port of the injector was held constant during testing, rendering gas momentum dependent only on mass flow rate, decomposition temperature, and chamber pressure.

At a CR of 3.0 the calculated momentum ratio, assuming the gas was at monopropellant chamber pressure, ranged from 2.8 to 14.0. The predicted difference in trajectory, according to the Wu et al. correlation, resulting from this range of momentum ratios is shown in Fig. 8. In the case of $Q = 2.8$ the fuel only penetrates about a quarter of the distance to the centerline of the chamber before breakup. For $Q = 14.0$ the fuel penetrates slightly more than halfway to the centerline of the chamber before column breakup. Both of these trajectories achieved a no-autoignition result even though the penetration differed significantly. Because the rest of the fuel trajectories at a CR of 3.0 are contained somewhere between those shown in Fig. 8, it is difficult to determine the influence of jet trajectory on autoignition based on the conditions tested here. The Mach number of the decomposed gas was approximately 0.45 in the gas port for all tests at this CR. It should be noted that after autoignition the density of the decomposed gas increased.

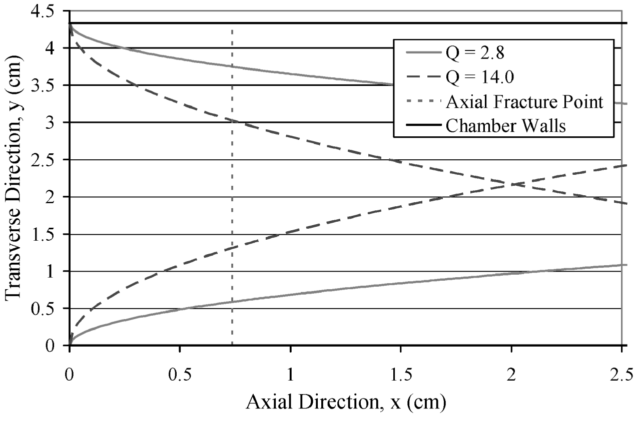

Fig. 8 Trajectory variations in tests run at a CR of 3.0.

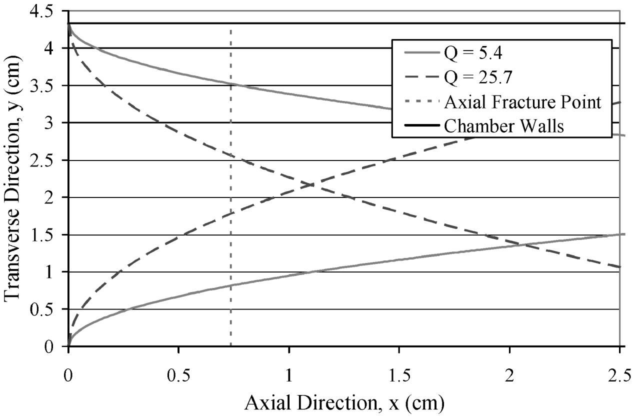

Fig. 9 Trajectory variations in tests run at a CR of 5.0.

At a CR of 5.0 the range of momentum ratio was calculated to be approximately 5.4 to 25.7. These trajectories are plotted in Fig. 9. The Mach number of the decomposed gas during these tests was approximately equal to 0.28. The test run at a minimum Q of 5.4 achieved strong autoignition. According to Fig. 9 the fuel jet penetrated only about one-third of the way to the centerline at this momentum ratio before breakup. No autoignition was achieved for the case of maximum Q of 25.7. Here the fuel penetrated very closely to the centerline before breakup. In this case, it is possible that fuel droplets from multiple jets could collide following breakup at the centerline, forming larger drops that take longer to vaporize. Also, when the fuel is centralized in the oxidizer port it may be more difficult to entrain into the shear-layer eddies; instead the fuel gets pushed downstream by the high-velocity freestream flow.

As previously explained, the throat diameter was decreased to increase the chamber CR from 3.0 to 5.0 while the flow rates were maintained at the same level to achieve the necessary equivalence ratio. This resulted in an increase in monopropellant chamber pressure and consequently a decrease in the velocity of the decomposed gas. Therefore, the calculated momentum ratios were higher at a CR of 5.0 than at 3.0, causing increased jet penetration. Similarly, to increase equivalence ratio, the H_2O_2 flow rate was decreased, dropping the monopropellant chamber pressure and gas velocity while correspondingly increasing the liquid-to-gas momentum ratio. As a result, jet penetration increased with increasing equivalence ratio. This effectively coupled trajectory effects to the effects of variations in equivalence ratio and CR.

Conclusions

An experiment was designed to investigate the autoignition of JP-8 in decomposed hydrogen peroxide. Independent test variables included chamber CR, equivalence ratio, chamber Mach number, and decomposition temperature. Results were obtained for H_2O_2 concentrations ranging from 85 to 98%, equivalence ratios from 1.4 to 2.8, and CRs of 3.0 and 5.0. Trends in experimental results agreed with those found in past autoignition studies. Test data showed that increasing hydrogen peroxide concentration, or decomposed gas temperature, increases autoignition limits at a constant CR. Autoignition was not achieved at equivalence ratios as low as 1.37 using 85% H_2O_2, whereas strong autoignition was achieved at equivalence ratios as high as 2.06 using 98% H_2O_2. However, the equivalence ratio was not the only factor that affected the autoignition boundary under the tested conditions. As a consequence of adjusting equivalence ratio at a constant H_2O_2 concentration through adjustments in oxidizer flow rate alone, monopropellant chamber pressure decreased with increasing equivalence ratio. This produced a coupled effect on autoignition between equivalence ratio and chamber pressure. Further tests are necessary to separate the influence of each factor.

Test data have also shown that increasing CR, or residence time, tends to increase autoignition limits. Strong autoignition was achieved at an equivalence ratio of 1.37 with 85% H_2O_2 at a CR of 5.0 whereas no autoignition was achieved at a CR of 3.0 at the same equivalence ratio. This is primarily a result of the increased shear-layer and chamber residence time. However, the monopropellant chamber pressure decreased with decreased CR, creating a coupling between CR and pressure effects. This was a result of increasing the throat diameter while maintaining identical mass flow rates. In addition, the drop in chamber pressure correspondingly increased the decomposed gas velocity upstream of the rearward-facing step. As a result, the shear-layer residence time decreased as well creating coupling of the two residence times. More tests, at a wider range of CRs, are necessary to specifically determine the effects of pressure and CR. In addition, future tests should be structured to separate the effects of shear-layer and chamber residence times.

The strong autoignition result at a CR of 5.0 contradicts earlier results where no autoignition was achieved using 85% H_2O_2 at a CR of 5.4 and an equivalence ratio around 1.4. It would be interesting to determine the specific difference in combustor designs that would cause the difference in the autoignition result. Fuel jet trajectory analysis suggested that overpenetration of the fuel jet would result in greater likelihood of no autoignition. However, more data are needed separating the trajectory variations from those of equivalence ratio and CR to conclusively determine the effect of jet trajectory on autoignition.

Future testing should also be structured to decouple the effects of pressure and equivalence ratio, pressure and CR, and to isolate trajectory effects from all other factors. To study the effect of equivalence ratio at a specific hydrogen peroxide concentration while maintaining a constant pressure, the oxidizer flow rate should be kept constant while varying the fuel flow. To investigate the effect of pressure while maintaining a constant equivalence ratio, both flows will need to be varied equally to maintain a constant mixture ratio. In addition, to determine the effect of chamber residence time, the chamber pressure will need to be maintained between CRs as well. This could be accomplished through variations in both the oxidizer and fuel flow rates. The main difficulty associated with this approach to the problem is that multiple fuel injectors are necessary to maintain appropriate fuel jet trajectories through each variation in flow rate, and it may be difficult to maintain constant trajectory during each manipulation. Another approach would be to maintain constant flow rates and throat diameter while adjusting chamber diameter. This would alter the step height, but the corresponding change in shear-layer residence time would be minimal compared to that of the chamber residence time. This approach would be rather expensive. More CRs should be tested as well to create a wider range of data on the effect of chamber residence time on autoignition. The effect of shear-layer residence time could be determined through variations in the rearward-facing step height, keeping all other geometry and flow rates constant. This would, of course, require the use of multiple injectors. In addition, it would be difficult to maintain a consistent jet trajectory. It would be interesting to vary the jet trajectory at constant operating conditions to determine trajectory and fuel distribution effects on autoignition. This would also require the use of multiple injectors.

Acknowledgments

This study was funded under grant number NAG4-227 through NASA Dryden Flight Research Center and the authors thank Nathan Palumbo, Technical Contract Monitor, for his support and technical advice. Financial support from the School of Aeronautics and Astronautics at Purdue University is also gratefully acknowledged. Pei-Kuan Wu is acknowleged for his technical assistance and advice. The authors extend their gratitude to machinists Madeline Chadwell, Jerry Hahn, Robin Snodgrass, and Rob McGuire for their many hours machining the test hardware for this project. Also Scott Meyer, Senior Engineer, deserves many thanks for his help in maintaining and upgrading the test stand at Purdue University's Advanced Propellants and Combustion Laboratory as well as for his assistance in all aspects of combustor testing.

References

[1] Ventura, M., and Mullens, P., "The Use of Hydrogen Peroxide for Propulsion and Power," AIAA Paper 99-2880, June 1999.

[2] Walder, H., and Broughton, L. W., "Thermal Ignition Tests of Hydrogen Peroxide and Kerosine in a 2200lb Thrust Rocket Motor," Royal Aircraft Establishment, RAE-TN-RPD-70, Aug. 1952.

[3] Andrews, D., "Rocket Engines for Satellite Launchers," *Proceedings from the International Symposium on Space Technology and Science*, AGNE Publ., Inc., Tokyo, 1966, pp. 111–120.

[4] Andrews, D., and Sunley, H., "The Gamma Rocket Engines for Black Knight," *Journal of the British Interplanetary Society*, Vol. 43, July 1990, pp. 301–310.

[5] Ventura, M., and Wernimont, E., "History of the Reaction Motors Super Performance 90% H_2O_2/Kerosene LR-40 Rocket Engine," AIAA Paper 2001-3838, July 2001.

[6] Wu, P. K., Fuller, R. P., Morlan, P. W., Ruttle, D. W., Nejad, A. S., and Anderson, W. E., "Development of a Pressure-Fed Rocket Using Hydrogen Peroxide and JP-8," AIAA Paper 99-2877, June 1999.

[7] Ross, R., Morgan, D., Crockett, D., Martinez, L., Anderson, W., and McNeal, C., "Upper Stage Flight Experiment 10 K Engine Design and Test Results," AIAA Paper 2000-3558, July 2000.

[8] Muss, J. A., Johnson, C. W., Kruse, W., and Cohn, R. K., "The Performance of Hydrocarbon Fuels with H_2O_2 in a Uni-Element Combustor," AIAA Paper 2003-4623, July 2003.

[9] Miller, K. J., Sisco, J. C., Austin, B. L., Martin, T. N., and Anderson, W. E., "Design and Ground Testing of a Hydrogen Peroxide/Kerosene Combustor for a RBCC Application," AIAA Paper 2003-4477, July 2003.

[10] Sisco, J. C., "Autoignition of Kerosene by Decomposed Hydrogen Peroxide in a Dump Combustor Configuration," M.S. Thesis, School of Aeronautics and Astronautics, Purdue Univ., West Lafayette, IN, Aug. 2003.

[11] Sisco, J. C., Austin, B. L., Mok, J. S., and Anderson, W. E., "Ignition Studies of Hydrogen Peroxide and Kerosene Fuel," AIAA Paper 2003-0831, Jan. 2003.

[12] Plee, S. L., and Mellor, A. M., "Characteristic Time Correlation for Lean Blowoff of Bluff-Body-Stabilized Flames," *Combustion and Flame*, Vol. 35, May 1979, pp. 61–80.

[13] Prior, R. C., Fowler, D. K., and Mellor, A. M., "Engineering Design Models for Ramjet Efficiency and Lean Blowoff," *Journal of Propulsion and Power*, Vol. 11, No. 1, 1995, pp. 117–123.

[14] Lin, K. C., Kennedy, P. J., and Jackson, T. A., "Penetration Heights of Liquid Jets in High-Speed Crossflows," AIAA Paper 2002-0873, Jan. 2002.

[15] Wu, P. K., Kirkendall, K. A., Fuller, R. P., and Nejad, A. S., "Breakup Processes of Liquid Jets in Subsonic Crossflows," *Journal of Propulsion and Power*, Vol. 13, No. 1, 1997, pp. 64–73.

[16] Edwards, T., Harrison, W. E., III, and Maurice, L. Q., "Properties and Usage of Air Force Fuel: JP-8," AIAA Paper 2001-0498, Jan. 2001.

[17] "Handbook of Aviation Fuel Properties," CRC Rept. 530, 1983.

[18] Freeman, G., "The Spontaneous Ignition Characteristics of Gaseous Hydrocarbon Fuel-Air Mixtures at Atmospheric Pressure," M.S. Thesis, School of Aeronautics and Astronautics, Purdue Univ., West Lafayette, IN, 1984.

[19] Spadaccini, L. J., and TeVelde, J. A., "Autoignition Characteristics of Aircraft-Type Fuels," NASA CR-159886, June 1980.

[20] Freeman, G., and Lefebvre, A. H., "Spontaneous Ignition Characteristics of Gaseous Hydrocarbon-Air Mixtures," *Combustion and Flame*, Vol. 58, Nov. 1984, pp. 153–162.

[21] Mestre, A., and Ducourneau, F., "Recent Studies on the Spontaneous Ignition of Rich Air-Kerosene Mixtures," *Combustion Institute European Symposium*, Academic Press, Inc., London, 1973, pp. 225–229.

[22] Walder, H., "An Investigation into the Thermal Ignition of Hydrogen Peroxide and Kerosine," Royal Aircraft Establishment, RAE-R-RPD 7, May 1950.

[23] Walder, H., "Further Investigations into the Thermal Ignition of Hydrogen Peroxide and Kerosine," Royal Aircraft Establishment, RAE-TN-RPD-43, Dec. 1950.

[24] Walder, H., and Purchase, L. J., "The Influence of Injector Design on the Thermal Ignition of Hydrogen Peroxide and Kerosene," Royal Aircraft Establishment, RAE-TN-RPD-80, April 1953.

[25] Coxhill, I., Richardson, G., and Sweeting, M., "An Investigation of a Low Cost HTP/Kerosene 40N Thruster for Small Satellites," AIAA Paper 2002-4155, July 2002.