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Reactive Stream Separation Photography

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High-speed photographic techniques were used to study impinging streams of nitrogen tetroxide and hydrazine in an experimental investigation of reactive stream separation. The high-resolution color motion pictures obtained show the detailed behavior of the liquid streams, spray fan, and individual droplets within the combustion zone. For the first time, reactive stream separation was shown to result from a cyclic phenomenon in which the streams meet, form a spray fan, are literally blown apart by a detonation or explosive deflagration, and then reform. Blowapart frequencies and magnitudes were correlated with jet diameters and injection velocities.

Introduction

Direct impingement of liquid streams can be used as an efficient means of mixing two liquids as well as atomizing them. This technique has found frequent application with liquid rocket engines. As first reported (1959) by Elverum and Staudhammer,[1] however, impinging hypergolic liquid streams may, under certain conditions and probably as a result of their chemical reactivity, tend to separate or be blown apart rather than achieving the intended degree of mixing.

Continued experimental investigation by Johnson, Riebling, et al.,[2-7] of impinging jets or sheets of nitrogen tetroxide and hydrazine in baffled or divided chambers, confirmed Elverum's photographic indication of fuel/oxidizer stratification. By auxiliary injection of fuel and oxidizer downstream of the chamber divider, performance changes could be used to monitor the presence of unmixed propellants from the main injection element. This work showed that the incidence of separation was dependent upon orifice sizes, becoming more pronounced as the orifice size was increased.

Since 1966, interest in blowapart or reactive stream separation, as it has alternately been called, was evidenced by both in-house and contractual work by NASA-JPL, NASA-LeRC, and by the Air Force (AFRPL). Most of the experimental methods have involved photography[8-12] in which color stratification in the combustion zone downstream of the propellant impingment location was interpreted to signify blowapart.

Kushida and Houseman[13] made a first attempt to develop an analytical model to predict when separation would or would not occur. This model included two regimes, depending upon the pressure of the environment. At low-to-moderate pressures, separation was presumed to result from liquid/liquid interfacial reaction and was thus dependent upon a residence time as indexed by the jet diameter divided by the injection velocity (D/V) and upon the propellant injection temperature. At some higher pressure, the value of which depended upon D/V, a gas phase reaction was presumed to sustain the liquid stream separation. Lawver, Breen, et al.[8] obtained still photographic data which seemed to verify the significance of D/V and propellant temperature. Their semiempirical model, developed somewhat differently from that of Kushida, emphasized the strong effect of liquid temperatures through an Arrhenius reaction rate expression. Unfortunately, however, as reported by Zung,[9] much of the Ref. 8 data are now considered questionable due to oxidizer boiling as it was injected and to propellant reaction with lucite windows of the experimental apparatus.

In summary, by the summer of 1969, blowapart was widely recognized as a phenomenon that should be characterized for the injector designer. However, design and operating conditions conducive to separation had not been adequately delineated, even for the much-studied nitrogen tetroxide/hydrazine system. Data for nitrogen tetroxide with other hydrazine-type fuels were sparse. No photographic techniques had yet been demonstrated that could provide uncontroversial data as to when separation did or did not occur. The physical nature of the separation process, when it did occur, was generally presumed to involve a quasi-steady lamination of the spray fans with fuel on one side and oxidizer on the other.

This paper provides the results of an experimental photographic study which for the first time dramatically describes

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Table 1 Summary of nominal injection conditions

Injector	Orifice diameter D, in.		Injection velocity V, fps		Resulting hydrazine
	Oxidizer	Fuel	Oxidizer	Fuel	D/V, sec
1	0.030	0.030	20–65	25–82	$0.3\text{–}1.0 \times 10^{-4}$
2	0.072	0.072	38–51	50–65	$0.9\text{–}1.2 \times 10^{-4}$
3	0.173	0.173	28–33	35–43	$3.3\text{–}4.1 \times 10^{-4}$

a cyclic blowapart phenomenon in which explosions disrupt the spray fan and drive the jets apart, thereby producing temporary, but vigorous, physical separation of fuel and oxidizer.

Experimental Apparatus

Test Apparatus

The experimental approach employed to obtain a description of reactive stream blowapart included both still and motion picture film coverage of injector elements under hot-fire conditions. The test hardware for the program included a series of bipropellant injectors mounted to accommodate open air firings.

Criteria for injector design were based on the desire to operate under conditions ranging from those in which good propellant mixing occurs to those which result in stream separation. Three injector configurations with substantially different orifice sizes (Table 1) were thus employed. All injectors were single-element, unlike-doublet-type configurations. The impinging stream included angle was 60° for injectors 1 and 2 and 45° for injector 3. Nominal operating conditions for all injectors included a mixture ratio (ratio of oxidizer to fuel flowrate) of 1.2 and a velocity ratio (V_0/V_f) of 0.84.

Smooth stainless steel tubes with L/D values of 100 (L/D is the ratio of the orifice length to its inside diameter) were employed to eliminate uncertainties with regard to hydraulic effects by providing fully developed turbulent flow and uniform, well-formed jets.

A schematic of the over-all test apparatus is shown in Fig. 1. Test equipment includes propellant run tanks, propellant feed system plumbing, propellant temperature conditioning baths, and an enclosure mount for the injector.

Photographic Apparatus

A schematic of the apparatus used for still photography is shown in Fig. 2. The top light was focused to produce a small diameter beam resulting in a high irradiance within the spray volume to be photographed. Also, the spray was illuminated from an oblique front angle. A third lamp was used for backlighting the spray. The Xenon flash lamps used for front, oblique, and backlighting were General Radio Stroboslaves, Type 1539-A. The electrical energy input per flash for these lamps was about 0.4 joule with a 3-μsec flash duration. The top light was provided by an EG&G FX-11 Xenon lamp and Model 501 Stroboscope power supply. The input energy per flash was 1.28 joules, which yielded manufacturer's rated light outputs of 4.0 mjoules per steradian. The flash duration was approximately 3 μsec. The three flash lamps were triggered simultaneously by a trigger signal supplied by the flash synchronization switch on the camera shutter. Photographs were initially taken on 4 × 5 in. polaroid film, and after satisfactory results were obtained, higher resolution film such as Ektachrome D was used. The combustion flame light was filtered out of the picture by use of a Kodak Wratten filter Type 34.

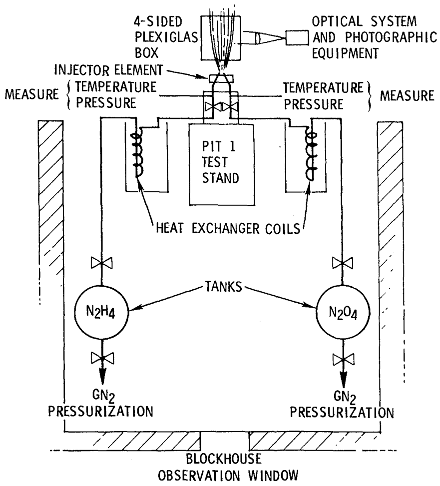

Fig. 1 Over-all blowapart facility schematic.

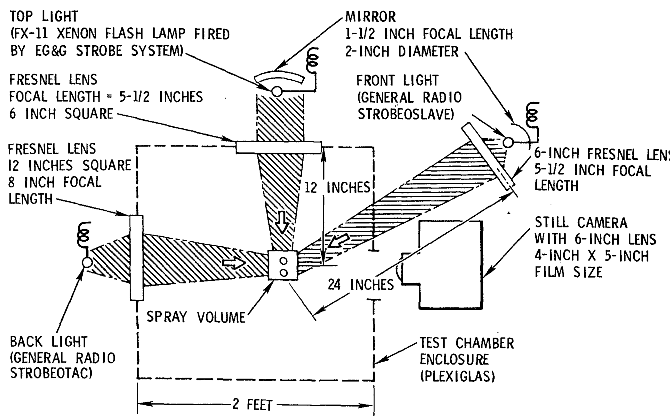

Fig. 2 Multiple light source photographic apparatus test setup for enhanced top and front lighting.

Figure 3 shows the photographic arrangement used for high-speed photography. The backlight flash lamp was an EG&G FX-3 spiral lamp driven by a Type 501 stroboscope power supply. The oblique light was an FX-11 flash lamp driven by a seond Type 501 stroboscope power supply. A prismless Fastax camera was used with Ektachrome EF film. The stroboscopes were synchronized with the camera to flash once each time the film advanced one frame.

Because of the 1/5000-sec exposure of the film, no filter was required to eliminate the flame light. The actual exposure of the drops to backlighting was between 2 and 3 μsec.

Experimental Results

Experiments with the 0.030-in.-diam Orifice Pair

Tests with the 0.030-in.-diam orifice pair were conducted over a range of D/V values from 0.3×10^{-4} to 1.0×10^{-4} sec with propellant temperatures of approximately 40°F. Propellant mixing was characteristic on all tests. This conclusion

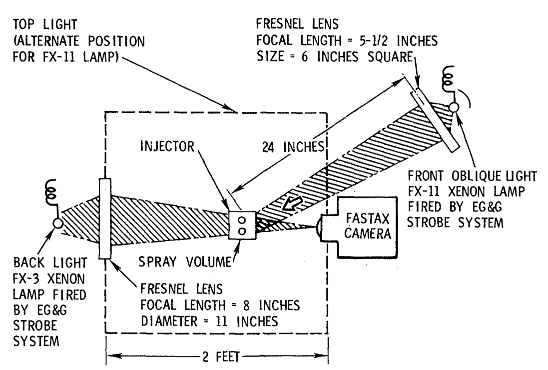

Fig. 3 Photographic apparatus for Fastax photography.

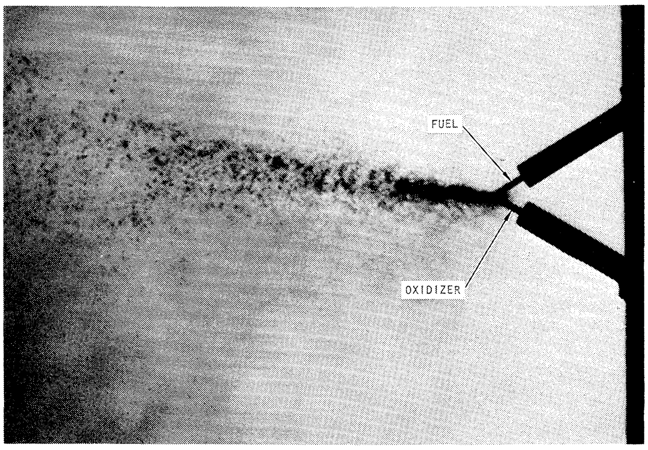

Fig. 4 Burning spray from N_2O_4/N_2H_4 impinging doublet, 0.030-in.-diam orifice element, edge view of spray fan from injector face to 4 in. downstream.

was reached by visual examination of the photographed spray fan (edge view).¶

Still photographs from each of an extensive set of tests indicated the presence of a well-developed spray fan without any indication of stratification or separation of propellant species. Qualitatively, this fan was the same as would be expected with nonreactive liquid streams. A typical photograph is presented in Fig. 4.

Experiments with the 0.173-in.-diam Orifice Pair

A cyclic blowapart was suggested by still photographs obtained with tests of the 0.173-in.-diam orifice pair. Thus, further observations were made using high-speed (2500 frames/sec) Fastax photograph. All high-speed photography applied to the 0.173-in.-diam orifice pair, including fan edge views and fan views at 4 and 6 in. downstream, revealed a cyclic-type propellant blowapart phenomenon. The propellant blowapart was characterized by flashes, possibly detonations or explosive deflagrations, occurring approximately 5 to 10 msec apart, although the frequency was irregular. There was no warning in the prior frames that the disturbances were about to occur. Thus, the disturbances develop over a period of time less than the 0.5-msec interval between frames.

A typical sequence of the blowapart process with the 0.173-in. orifice pair is shown in Fig. 5. This phenomenon may be characterized by the following repetitive sequence of events. 1) Formation of a spray fan similar in shape to that formed by nonreactive liquids. During this period, the propellants remain in contact and are "mixed," at least within the small dimension corresponding to the spray "sheet" thickness. 2) Explosions occur which gasify virtually the entire spray field and literally blow the jets apart and back toward the injector face. Following this, separate clouds of fuel and oxidizer droplets move downsteam without mixing. 3) The jets gradually reform and again develop a spray fan.

A few instances were also observed in which a weak blowapart occurred, which differed in that only a small section of the spray fan would be consumed in the explosion.

Experiments with a 0.072-in.-diam Orifice Pair

Cyclic blowapart was also found with the 0.072-in.-diam orifice injector. The sequence of events observed portrayed an event analogous to that prevalent with the large element. The weak blowapart, as illustrated in Fig. 6, occurred more frequently, however. Occasional small "puffs" were also seen. These three types of disturbances are sufficiently different to be classed as distinct disturbance types. There does not appear to be a continuous transition from one type to the other, although the mechanisms must be presumed to be closely related.

In Fig. 7, the bar chart illustrates quantitatively the variation in frequency at which the different disturbance types occurred. The upper bar was obtained by counting the disturbances obtained in approximately one second with the large diameter orifice pair. With the intermediate size injector (orifice diameter 0.072 in.) at approximately the same injection velocities (V_0 and V_f were approximately 38 and 50 fps, respectively) the over-all incidence of disturbances was reduced and, of these events, substantial portions represented weak blowapart and puffs. The lower bar represents the results obtained with the intermediate size injector element, but with the oxidizer and fuel velocities, respectively, increased to 51 and 63 fps. Clearly, a very substantial further decrease in the incidence of blowapart was obtained.

From the motion picture film it was also possible to determine the percentage of time during which the fuel and oxidizer jets are in contact (mixed). As suggested in Fig. 8, this time appears to decrease approximately linearly with D/V.

Discussion

Nature of the Disturbance

Throughout this discussion the word "disturbance" has been used because of uncertainty regarding the detailed nature of the phenomenon that blows apart the injected propellant streams or disrupts the spray fan. For the larger injection element the wavefront associated with the disturbance seemed to move across and beyond the (camera) field of view in a time short compared to the frame-to-frame period. Its velocity cannot, therefore, be less than about 400 fps, but it may be much higher than this. Therefore, conceivably, this may be a detonation. With the intermediate size injector, spherically shaped bursts of shattered propellant spray are

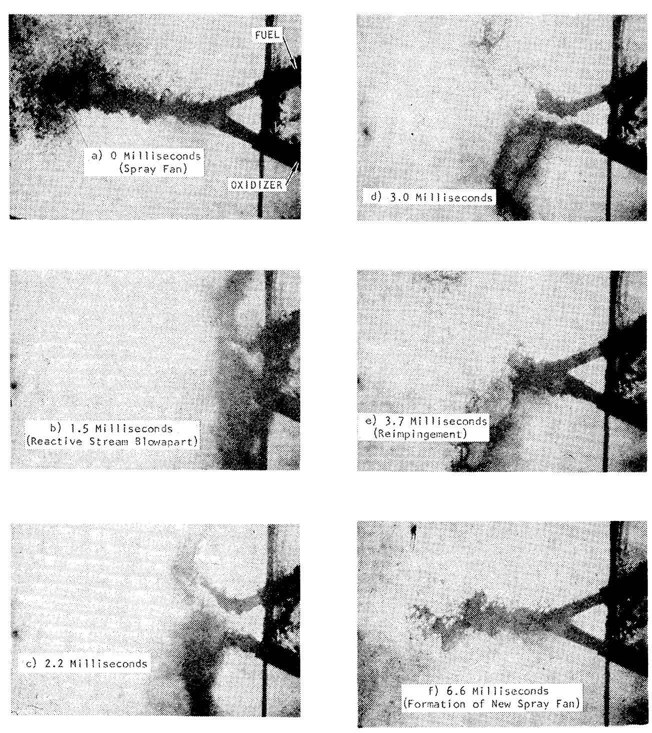

Fig. 5 Typical sequence showing cyclic behavior of N_2O_4/N_2H_4 reactive stream blowapart with 0.173-in.-diam unlike impinging stream orifice pair element, edge view of spray fan from injector face to 4 in. downstream, $D/V = 4.0 \times 10^{-4}$.

¶ "Edge views" are obtained from a direction perpendicular to the plane of the two impinging jets and show the narrow dimension of the spray fan. Fan views are oriented 90° from the edge view and show the broad side of the fan.

characteristically seen. These can be seen in successive frames, growing relatively slowly. These may represent some type of explosive deflagration, although this conclusion is only speculative.

The observed characteristics are consistent with the following hypothesis. 1) An initial disturbance occurs. This may be explosion of hydrazine azide[14] or perhaps the detonation of a pocket of mixed propellant vapors within the core of the spray fan. The size of this explosion depends on operating conditions such as jet diameters, velocities, etc. 2) The net effect depends on the size of the initial explosion. If it is very weak, the results would be shattering of spray within a limited zone. Above a critical size, the spray field may respond and support the initial disturbance, which could grow as an explosive deflagation or develop into a detonation.

Comparison with Other Investigations

In earlier investigations, Clayton[15] and Burrows[7] noted the presence of popping or oscillatory combustion associated with the impingment region of nitrogen tetroxide/hydrazine streams. However, in their photographs the flame light obscured the behavior of the streams, the spray fan, and the droplets. In 1969, under a study of pops and spikes, Mills, et al.[16] presented some frames taken from high-speed movies that illustrate what they called "injection mixing explosions." Though their photographs contain far less detail than those presented here, the phenomena illustrated can now be recognized as the types of blowapart and weak blowapart disturbances previously discussed. However, they were not recognized as being responsible for separation in the Ref. 16 report.

The data obtained in this program present a substantial advance in investigation of reactive stream separation phenomena in that 1) the cyclic nature of the blowapart process is so clearly illustrated, and 2) significant physical separation of fuel and oxidizer spray can be seen to result from blowapart.

Prior to this investigation, the prevalent view of reactive stream separation was that it was a quasi-steady process. This is reflected in the approach used by essentially all previous experimenters as can be seen by reference to the literature cited in the Introduction of this paper. The same view is evident also in all published attempts at analytical modeling. The question that now must be answered is whether a significant quasi-steady separation really occurs at all, or whether a cyclic process as observed in the present work is responsible for all true reactive stream separation. Certainly all previous data should be re-evaluated in recognition of the time dependence of the blowapart process.

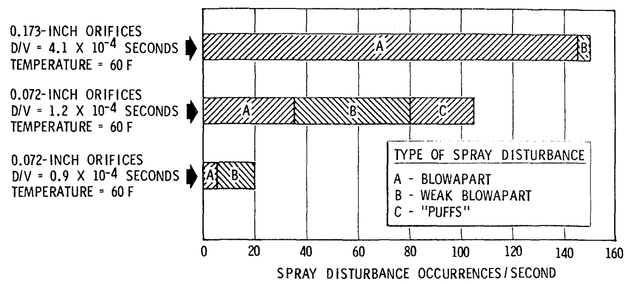

Fig. 7 Number and type of spray disturbance occurrences/sec for varying residence time (D/V).

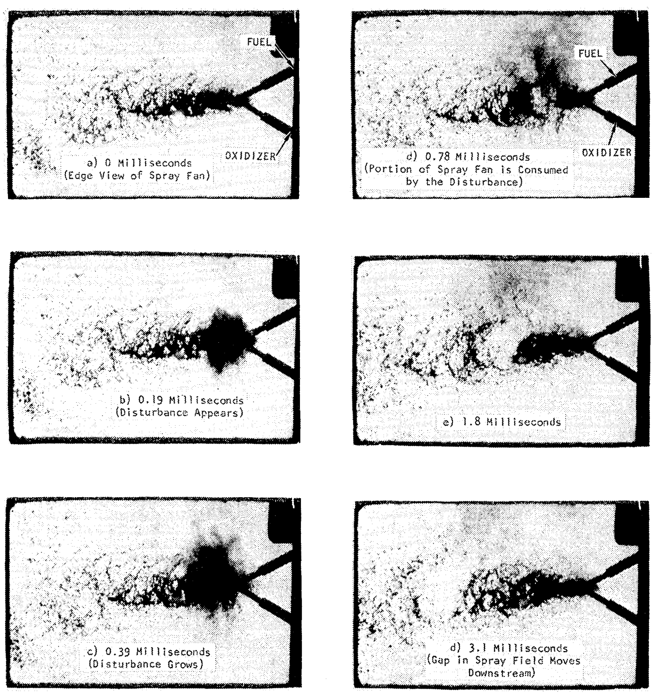

Fig. 6 Typical sequence showing cyclic behavior of N_2O_4/N_2H_4 reactive stream weak blowapart with 0.072-in.-diam unlike impinging stream orifice pair element, edge view of spray fan from injector face to 4 in. downstream, $D/V = 1.2 \times 10^{-4}$.

Conclusions

The most important conclusion based on the program results is that reactive stream separation can result from a cyclic blowapart process in which repeated explosions disrupt the spray fan and drive the jets apart, thereby producing temporary physical separation of fuel and oxidizer. Between these disturbances a normal spray fan forms, in which the propellants are not separated. As operating conditions (such as orifice sizes and injection velocities) vary, there is not an abrupt transition from mixed to separated streams. Instead, the frequency and strength of the disturbances change gradually, so that the proportion of the time when the propellants are mixed varies.

A second conclusion is that the injector designer is in worse shape with regard to guidelines for avoidance of or compensations for reactive stream separation than previously thought. Previous experimental work intended to provide such information must now be reinterpreted with consideration of the time dependence of the physical process. The value of still photographs is particularly open to question.

A third and final conclusion is that high-speed motion picture photography as applied in this program with appropriate backlighting, toplighting and other photographic techniques is an extremely valuable method for experimental investigation of blowapart.

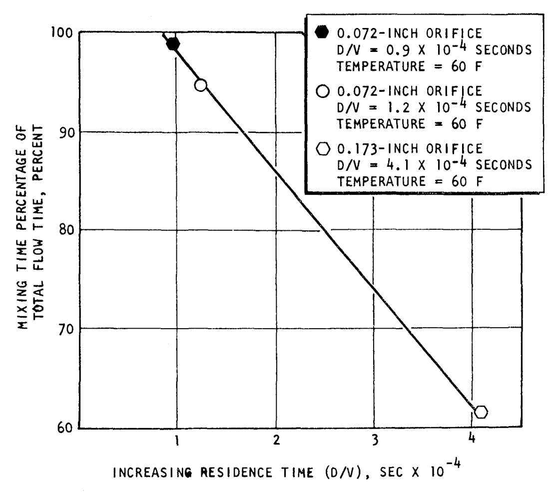

Fig. 8 Correlation of percentage of time propellants mix as a function of residence time (D/V).

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Spectral Infrared Reflectance of H_2O Condensed on LN_2-Cooled Surfaces in Vacuum

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Absolute hemispherical-angular reflectance measurements were made for H_2O cryodeposits formed in a vacuum infrared integrating sphere. These deposits were condensed on cryogenically cooled black epoxy paint and polished stainless steel surfaces at pressures between 2×10^{-2} and 4×10^{-2} torr. The results obtained are presented as functions of view angle from 0° to 60°, deposit thickness from 0 to 4.0 mm, and wavelength from 0.5 to 12.0 μ. All three structural forms of ice *I* (hexagonal, cubic, and amorphous) were observed with the form occurring being a function of cryosurface temperature. The reflectance of any H_2O deposit was found to be strongly dependent on the form of ice present. From the results obtained in this investigation important conclusions are drawn with regard to effects on cooled optics and space simulation studies in ground test facilities.

Introduction

In the fields of space simulation, radiative transfer, planetary environments, etc., there are numerous reasons for interest in the optical properties of ice, frost, or cryodeposit. For example, in space simulation testing of cryogenically cooled detectors, the condensation of H_2O on cooled mirrors, windows, and lenses or on the test chamber cryowall can be undesirable as the condensate may alter the thermal radiative properties of these surfaces. Additionally, the reflectance, transmittance, and emittance of H_2O frost are of

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Index Categories: Radiation and Radiative Heat Transfer; Thermal Surface Properties.

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