the mass at LEO can be delivered usefully to GEO with technology that is based on present capabilities.

Variation of Mission Requirements

If the capacitor lifetime depends only on the number of shots, then higher power missions (shorter transfer times) can be accomplished simply with higher repetition rates and/or longer current pulsewidths. That is, to the extent that the capacitors dominate the specific mass, $\alpha\tau(=EN)=$ constant. The optimum specific impulse is also constant, so the delivered mass fraction depends only on the necessary Δv for the mission.

The size of the capacitor supply will increase with the size of the mission payload. For fixed transfer time, the average thrust required will also increase with payload mass. Since the number of shots N is set by the capacitor lifetime, the repetition rate is fixed in this case and the current pulsewidth increases with the mass of capacitors.

Recent experiments[5] indicate that plasma flow conditions similar to the PPT flow can be maintained for the length of the current pulse in a two-stage thruster system. This system uses an actual microthruster (for the LES 8/9 mission) to initiate current flow in an ablation thruster driven by a pulse forming network. The arrangement is shown conceptually in Fig. 1. Data suggest that after the initial microthruster plasma clears the second-stage, quasi-steady exhaust speeds of $1.7\text{-}2.5 \times 10^4$ m/s are achieved for the remainder of the flat-topped current pulse (~ 160 μs). The impulse per discharge appears to scale with system energy over an order of magnitude variation in PFN energy. Preliminary estimates of kinetic efficiency divided by input electrical energy indicate an efficiency of 23-72%. It would thus appear possible to vary current pulsewidth and maintain useful efficiency at a specific impulse of about 2000 s.

Concluding Remarks

From earlier work on pulsed plasma microthrusters and recent efforts involving extended, constant current waveforms, the technology for a family of pulsed plasma thrusters could reasonably be applied to near-Earth missions, including orbit transfer. Such a family would allow electric propulsion to be introduced into the U.S. inventory in an evolutionary manner as space-electrical power becomes available.[8] In particular, it appears that an ablation arc on a Teflon slab, with combined electrothermal and electromagnetic contributions to thrust, provides an adequate propulsion mechanism in the I_{sp} range of 2000 s. Such an arc can be operated in both pulsed and quasi-steady conditions indicating that thruster physics can be maintained as prime-power levels extend from kilowatts to megawatts. Operational experience could thus be shared within this family of thrusters, providing confidence in performance as higher power missions are defined. Such confidence is probably critical to the practical introduction of electric propulsion in U.S. space missions over the next few decades.

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Explosion Phenomenon from Contact of Hypergolic Liquids

Masafumi Tanaka,* Wataru Daimon,† and Itsuro Kimura‡
University of Tokyo, Tokyo, Japan

Introduction

THE phenomenon of explosions induced by the contract of hypergolic liquid propellants has potential importance for the combustion process in rocket engines and for safety procedures. Friedman et al.[1] conducted experiments on the mechanisms of the explosions, using a falling droplet apparatus and specially designed devices to observe the process with a high-speed camera (up to ~ 7000 frames/s).

Based on sequences of ultrahigh-speed motion pictures having a sufficient power of resolution ($\sim 10^5$ frames/s) and experimental observations of the characteristics of the explosion, such as the strength of the shock waves produced and the time lags of their occurrence, we suggested in Ref. 2 that the explosion in the case of a N_2H_4 (droplet)/N_2O_4(pool) system is caused by a sudden gasification of the thin surface layer of N_2O_4.

In the present investigation, we took ultrahigh-speed motion pictures of the explosion in the reversed system [N_2O_4(droplet)/N_2H_4(pool)]. The fluid dynamical process from the contact of the two liquids to the occurrence of an explosion was investigated in detail and compared with records of the N_2H_4(droplet)/N_2O_4(pool) system. There are marked differences between the properties (i.e., density, surface tension, boiling point, etc.) of N_2H_4 and N_2O_4.

Experimental Procedure

The experimental apparatus was similar to that described in Ref. 2. A Beckman and Whitley ultrahigh-speed camera was equipped with a xenon flash lamp having a delay circuit that could be operated for the required lighting period. Because the explosion induced by the contact of the hypergolic propellants could not be reproduced consistently, the time lag was varied in each test run. Thus, it was difficult to obtain the ultrahigh-speed motion pictures of the explosion phenomenon (the operating time of the high-speed camera was only 0.5 ms at 10^5 frames/s) and we had to accept the low possibility for obtaining successful records.

Results and Discussion

A selected run of high-speed motion picture records for the N_2H_4(droplet)/N_2O_4(pool) system is shown in Fig. 1. It was

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*Graduate Student, presently Research Associate, Department of Aeronautical Engineering, The National Defence Academy, Yokosuka, Japan.

†Presently Research Scientist, Department of Physics, School of Medicine, Nihon University.

‡Professor, Department of Aeronautics, Faculty of Engineering.

observed that the explosion time lag (the time between the contact of the two liquids and the occurrence of the explosion) scattered widely (0.1 ~ 0.6 ms), although in the case shown in Fig. 1 it is 140 μs. Optical observation of a colliding system of the droplet/pool of hypergolic liquids is rather complicated. However, in the photographs shown in Fig. 1, which were taken with a parallel backlight, we can observe the aspect of the pool surface, which faces the surface of the submerged part of the droplet through a vapor layer. It is seen in Fig. 1 that the surface of the pool (N_2O_4), which is depressed with the lapse of time, appears as a sharp boundary until the 118 μs frame. In the 129 μs frame, however, a dispersed layer has formed on the surface of the depressed pool and, in the 140 μs frame, the explosion occurs. It is interesting to note that this thin dispersed layer forms in a very short time (less than 5 μs) uniformly along the depressed surface of the pool.

Figure 2 shows a schematic explanation of the high-speed motion pictures shown in Fig. 1. The pool surface, being depressed with the lapse of time [thick solid lines I(108 μs), II(118 μs)] is expected to locate at the position of thick broken line III′ in the 129 μs frame if no special phenomenon occurs. In the 129 μs frame, however, a dispersed layer is formed and the depressed pool surface is located at the position of thin solid line III. These motion pictures show that the turbulence due to the growth of interfacial instability has little influence on the dispersed layer; the dispersed layer appears much too quickly and the minimum value of the explosion time lag scarcely depends on the impact velocity.[2] It is reasonable to think that the behavior of the dispersed layer indicates the sudden gasification of a thin surface layer of N_2O_4 that is superheated by the heat transfer from the reacting vapor layer between the two liquids. (The 21°C boiling point of N_2O_4 is much lower than that of N_2H_4 at 113°C.)

Figure 3 shows a selected run of high-speed motion pictures for the reversed system [N_2O_4(droplet)/N_2H_4(pool)]. In this case, the explosion time lag also scatters widely (0.1 ~ 0.65 ms), just as it did in the N_2H_4(droplet) /N_2O_4(pool) system. Figure 4 is a schematic explanation of the high-speed motion pictures shown in Fig. 3. The pool surface is depressed with the lapse of time (thick solid lines I at 392 μs and II at 412 μs). In the 433 μs frame, where the surface is located at the position of thick solid line III, a dispersed layer is observed to be overlapping the line. A microscopic observation reveals that there is a noticeable difference between the dispersed layer seen in the 129 μs frame of Fig. 1 and that in the 433 μs frame of Fig. 3. In the former, a distinct boundary is observed between the dispersed layer and the pool liquid (N_2O_4). In the latter, the dispersed layer, which is thicker in the region near the side of the depressed pool surface, gradually becomes faint in the direction of the interior of the pool liquid (N_2H_4). The phenomenon, which is in progress in the 433 μs frame of Fig. 3, seems to be as follows. The surface layer of the lower boiling point N_2O_4 droplet suddenly gasifies (the droplet surface cannot be observed in the photograph) and the vapor produced penetrates through the depressed pool surface.

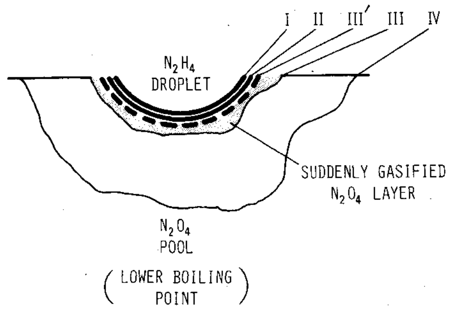

Fig. 2 Explanation of the explosion phenomenon observed in Fig. 1.

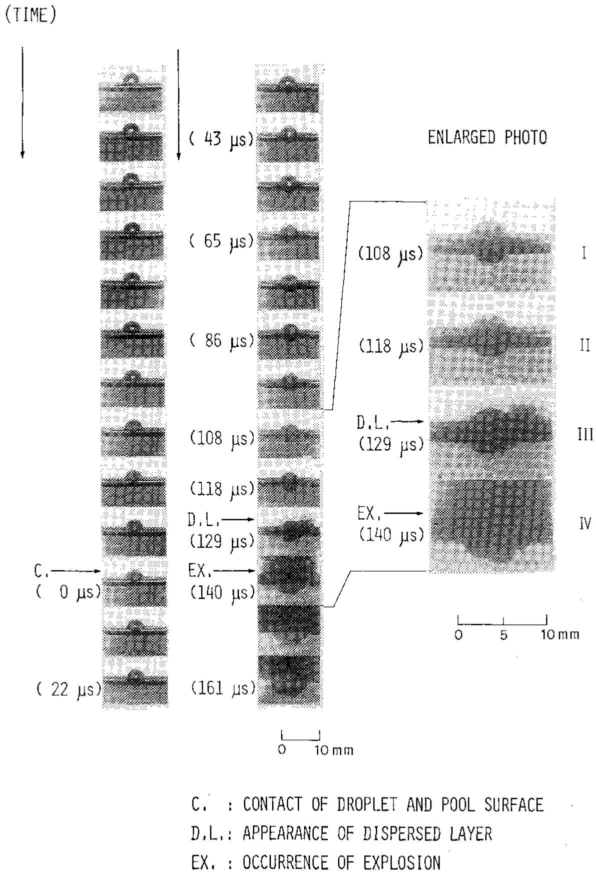

Fig. 1 High-speed motion pictures of the explosion in the N_2H_4(droplet)/N_2O_4(pool) system (92,900 frames/s, $D = 4.6$ mm, $V = 3.5$ m/s).

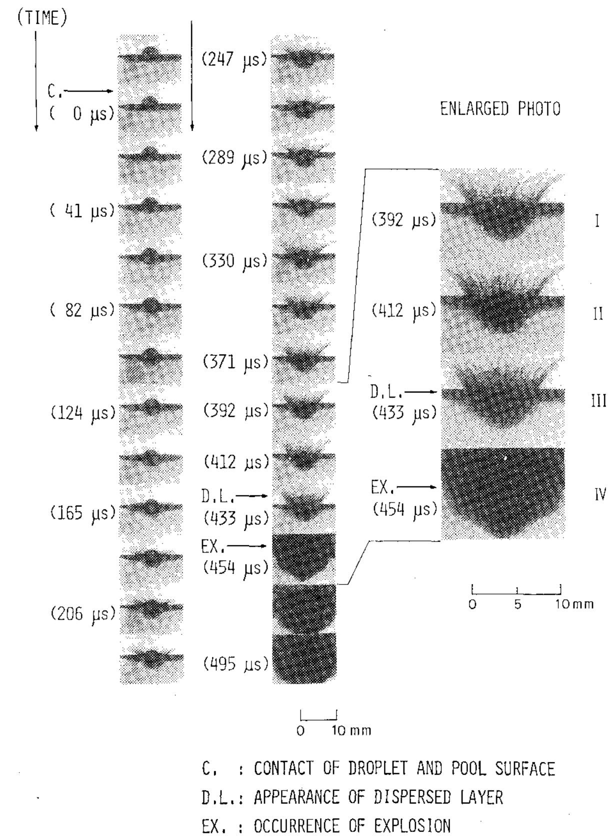

Fig. 3 High-speed motion picutres of the explosion in the reversed system [N_2O_4(droplet)/N_2H_4(pool)] (48,500 frames/s, $D = 3.9$ mm, $V = 3.5$ m/s).

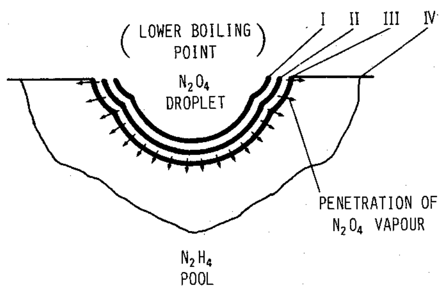

Fig. 4 Explanation of the explosion phenomenon observed in Fig. 3.

It is well known that, when nonreactive droplets interact with a pool surface, a splash appears around the droplet and that the main constituent of the splash is the pool liquid. In the present experiments, it was generally observed that in the N_2H_4(droplet)/N_2O_4(pool) system the splash hardly appeared, as can be seen in Fig. 1. One of the causes of this will be that the main constituent of the splash is N_2O_4, which has a high volatility.

Although there exists some difference between the fluid dynamical processes observed in the N_2H_4(droplet)/N_2O_4 (pool) and the reversed systems, it is seen that the probability of explosion and the strength of the explosion are nearly the same for the two systems.

Summarizing the results, it can be concluded that, for explosions induced by the contact of hypergolic liquids, more evidence has been obtained to support the presumption that the sudden gasification of the superheated surface layer of the more volatile liquid playes the role of a trigger.

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Simulation of Wake Passing in a Stationary Turbine Rotor Cascade

D. J. Doorly* and M. L. G. Oldfield†
University of Oxford, Oxford, England, U.K.

Introduction

FLOW unsteadiness has been found to exert a considerable influence on the aerodynamic and heat-transfer performance of turbomachinery blades. The most significant contribution to this unsteadiness is caused by "wake passing," the term used here to describe the flow produced on a downstream blade row as it periodically chops through the wakes shed by the upstream blade row. The effect occurs both in the compressor and turbine blade passages, and has been studied by Evans,[1] Walker,[2] and others, for the case of compressors. Turbine studies of the unsteady boundary layer on the rotor blade of a single-stage low-speed axial flow turbine have been performed by Dring et al.[3] and Hodson.[4]

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*Presently Postdoctoral Research Fellow, Mathematics Department, University College, London.

†Lecturer, Department of Engineering Science.

In cooled gas turbine blades the aerodynamic fluctuations due to wake passing may greatly affect the heat-transfer rates to the blade surface. Dunn and Hause[5] have performed some heat-transfer measurements on a small turbine stage.

Although these experiments have indicated that the effects of wake passing on turbine blades may be substantial, the mechanical complexities involved in obtaining measurements from a high-speed high-temperature rotating turbine stage have as yet precluded detailed boundary-layer and heat-transfer studies at Reynolds and Mach number conditions appropriate to large modern aircraft engines. The fully rotating experiment is not convenient for such detailed investigations. This is partly due to the problems of adequate instrumentation, and obtaining satisfactory flow visualization in rotating turbine stages. In the turbine, it is also difficult to vary independently parameters such as wake characteristics, and the spacing between the wakes.

This Note describes a new experiment that has allowed wake-passing flow to be generated in a stationary cascade of turbine rotor blades mounted in a short-duration wind tunnel. Examples are given of the flow visualization and unsteady heat flux results, obtained using a typical modern turbine blade profile operating at full-scale Reynolds and Mach numbers. Flexibility in the experimental design has allowed effects of wake size, spacing, and combinations of wake passing and freestream turbulence to be assessed. In addition, by running the wake generator at subsonic and sonic flow-relative speeds, studies have been made of the effects of wake passing with and without associated shock waves. Schlieren flow visualization has been used to chart the progress of the wakes through the blade passages. This provides the time history of the wake in the external flow, and, coupled with the boundary-layer history provided by the unsteady heat-transfer and pressure measurements, has revealed the unsteady transition process responsible for the heat-transfer effects.

Rotating Bar Wake Generator

The unsteady flow at the inlet to a first-stage turbine can be reproduced at the inlet of a stationary cascade of rotor blades

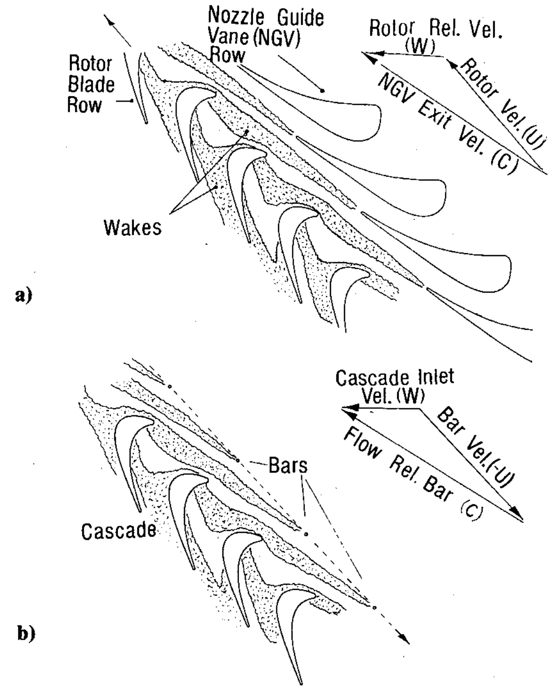

Fig. 1 a) The unsteady (wake-passing) flow in the blade passages of the first-stage turbine and b) the simulation of this flow in a stationary rotor cascade mounted in a wind tunnel by moving a row of wake-generating bars at the correct speed in front of the cascade.