low or moderate friction in vacuum; very high friction occurred only when both members were soft (copper and copper alloy, aluminum and aluminum alloy, silver, nickel), with the iron alloys of intermediate hardness (A286 and 4340) showing intermediate friction coefficients.

The ceramic vs metal combinations showed fairly low coefficients of friction, averaging 0.12 in space (Table 1). The harder member of each pair was, in these cases, extremely hard.

Combinations of metal vs metal with molybdenum disulfide lubricant and of polytetrafluoroethylene vs metal or ceramic gave the lowest coefficients, averaging 0.04 in space. Metal vs metal combinations with grease lubricant had somewhat higher friction. Metal vs metal with metal film lubricants averaged still higher friction; this may have been influenced by wearing away of the film. In all of the lubricated materials, the method of applying lubricant undoubtedly has an important effect.

The coefficients in space were not systematically different from those in laboratory vacuum (Table 1). It is possible that the pressure difference between the space and laboratory vacuums achieved was too small to bring out a difference in friction behavior. It also is possible that a difference in behavior was masked by differences between experiment assemblies. (The same assembly was not used in laboratory vacuum as in space, because it was desired to fly unworn disks and riders.) A more complete account of this work will be published at a later date.[3]

Conclusions

1) An experiment for measuring the coefficient of sliding friction for a number of material combinations was flown on the spacecraft Ranger 1 and 2. The apparatus functioned in space as designed, on both flights. Although the orbits attained were different from those planned, meaningful data were obtained from Ranger 1.

2) Under the conditions of the experiment (including vacuums of 8×10^{-9} to 3×10^{-6} mm Hg), polytetrafluoroethylene sliding against metals and ceramics, as well as metals sliding on metals with a molybdenum disulfide lubricant, appeared to have very low coefficients of friction, averaging 0.04. Ceramics sliding against metals, unlubricated, and metals sliding on metals with grease or gold-plate lubrication showed intermediate values, averaging 0.13. Unlubricated metals sliding on metals showed moderately high coefficients, averaging about 0.5; with some pairs, values above 1.0 were observed.

3) For unlubricated metals sliding against metals or ceramics, the friction coefficient tended to be low when at least one member of each pair was of high hardness.

4) The data were not inconsistent with the hypothesis that high coefficient of sliding friction between metals in vacuum can be correlated with high mutual solubility of the materials.

5) The friction coefficients measured in space, with exposure to vacuums of 8×10^{-9} to 2×10^{-6} mm Hg, were not, in general, systematically different from those measured in the laboratory at a vacuum of 5×10^{-6} to 1×10^{-5} mm Hg. For unlubricated metallic materials, the friction coefficients observed in vacuum generally were higher than those measured in air at shorter running times.

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Effect of Additives on Formation of Spherical Detonation Waves in Hydrogen-Oxygen Mixtures

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This paper deals with the initiation, by means of exploding wires, of spherical detonation in a gaseous mixture consiting of 62 mole % of hydrogen and 38 mole % of oxygen. The minimum electrical energy, stored in the condenser of the initiator circuit, needed for initiation of detonation is $E_i = 10.5 \pm 0.3$ joules, in agreement with results reported in the literature. The effect of up to 5% of various gases, added to this hydrogen-oxygen mixture, on E_i is studied. It is found that, while some gases inhibit the formation of detonation ($E_i > 10.5$ joule), others promote it ($E_i < 10.5$ joule). Of the additives studied in this program, the best inhibitor is isobutene; transbutene-2, propylene, and pentacarbonyl iron are also quite effective. The results are compared and contrasted with the related flame-inhibition experience. A mechanism is suggested to account for the inhibition.

Introduction

ACCIDENTAL spilling of large amounts of liquid hydrogen and liquid oxygen, such as might occur in either ground or flight use of rockets, resulting in rapid evaporation of the two liquids, presents a gas-phase detonation hazard. The aim of this work has been a quantitative study of the possible desensitizing agents by determination of the critical energy necessary for initiation of detonation, first in a pure hydrogen-oxygen mixture and then, in the same mixture, containing small amounts of various gaseous additives.

Initiation of detonation in gaseous mixtures of hydrogen and oxygen confined in tubes has been investigated extensively for many years.[1] The recent work has shown quite conclusively that the process of transition of a flame to detonation depends essentially on hydrodynamic interactions of the gas with the confining walls.[2–4] Therefore, if the length of the tube and the conditions of confinement are adequate, the minimum energy that must be supplied externally for initiation of detonation is not necessarily larger than that needed to establish a slow flame, which is usually only a fraction of a millijoule. On the other hand, the amount of energy needed to initiate a (spherical) detonation wave purely in the gas phase, without the benefit of interacting solid surfaces, is many orders of magnitude higher.[5–9] Litchfield[8] found that, if such a detonation wave is initiated by means of an exploding wire, the critical energy needed for initiation in the stoichiometric hydrogen-oxygen mixture, initially at 1 atm, is 13 joules. The critical energy obtained with other ignition sources is even higher.[6, 8]

Experimental Procedure

The apparatus used was fashioned after the one described by Litchfield.[8] The reaction was initiated in the center of a stainless-steel bomb, 19.2 cm in diameter, by explosion of a copper wire, 1-cm long, and 0.079-mm thick. The wire

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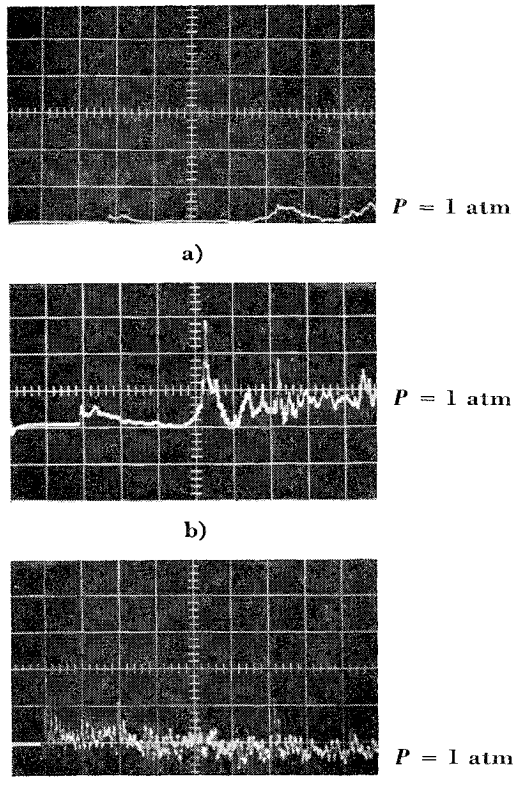

Fig. 1 Pressure history at the wall of the bomb. Horizontal scale: 50 μsec/grid line. Vertical scale: 17 atm/grid line. Sweep is triggered by explosion of wire at $t = 0$.

was exploded by a rapid high-voltage pulse through a thyratron circuit from a 0.94-μf condenser. The condenser could be charged up to 10 kv, which corresponds to a stored energy of 47 joules.

The pressure at the wall of the bomb (i.e., 9.6 cm from the source of initiation) was recorded by a piezogage continuously from the instant of explosion of the wire. Occurrence of detonation was judged by both the arrival time and the approximate amplitude of the first pressure pulse at the wall, as illustrated by the oscilloscope records in Fig. 1.

A record of detonation failure, typical of relatively low initiation energies, is shown in Fig. 1a. The arrival time of the first pressure pulse, 135 μsec, corresponds to an average propagation velocity of 0.71 mm/μsec, which is much less than the steady-state detonation velocity of 2.7 mm/μsec. The amplitude of the first pulse is only about 4 atm; indeed, the pressure throughout the record remains at a fraction of the reflected detonation pressure (about 40 atm).

Figure 1b, corresponding to an initiation energy only slightly short of critical, not only shows a relatively long first-transit time and a subdetonation pressure amplitude of the first pulse, but also shows the amplitude of the second pulse to be approximately that of a steady-state detonation wave. Detonation evidently occurred as a result of convergence of the first reflected wave at the center of the bomb. Since detonation occurred only after reflection, this shot did not satisfy the criterion of gaseous detonation either.

The record in Fig. 1c is typical of the shots in which the detonation wave developed in the gas phase before the first wave reached the wall. While the pressure amplitude in this type of record is of the expected order of magnitude for steady-state detonation, it cannot be read accurately, because the head-on impact of the detonation wave with the piezocrystal causes strong mechanical vibration of the pressure gage.

All the results reported below were obtained with a somewhat fuel-lean mixture consisting of 62 parts of hydrogen and

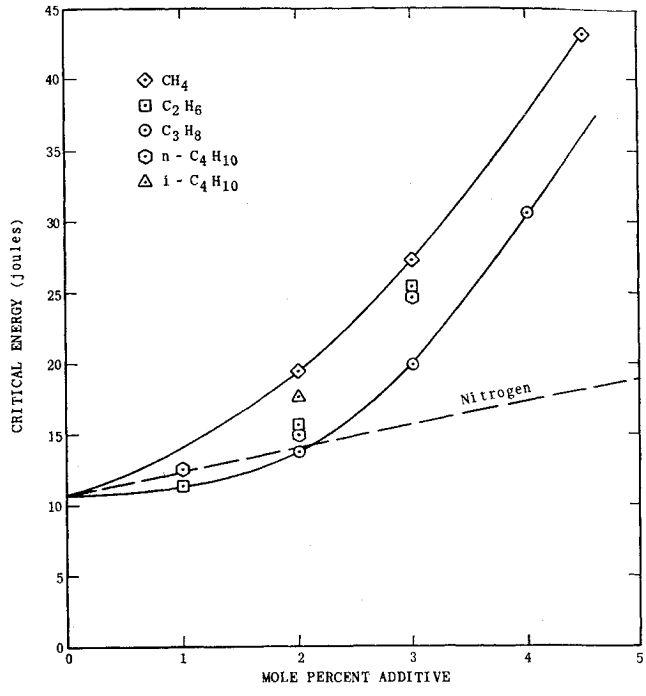

Fig. 2 Effect of alkanes, added to the mixture consisting of 62% H_2 and 38% O_2, on the critical energy for initiation of spherical detonation.

38 parts of oxygen by volume, with small amounts (1–5%) of additives. The gases were thoroughly mixed before being admitted to the evacuated bomb. The initial state of the gaseous mixture, in all tests, was 1 atm of pressure and room temperature (21–26°C). The reported critical initiation energies are the electrical energies stored in the condenser. Most data are accurate within ±5%.

Results

For initiation energies above the critical (see Fig. 1c) the measured delays from the explosion of the wire to the arrival of the detonation wave at the wall varied from 38 to 65 μsec

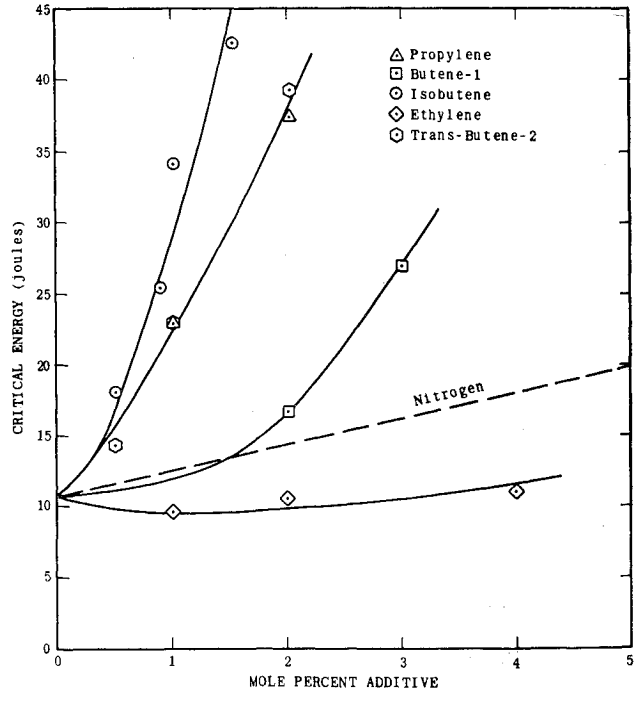

Fig. 3 Effect of alkenes, added to the mixture consisting of 62% H_2 and 38% O_2, on critical energy for initiation of spherical detonation.

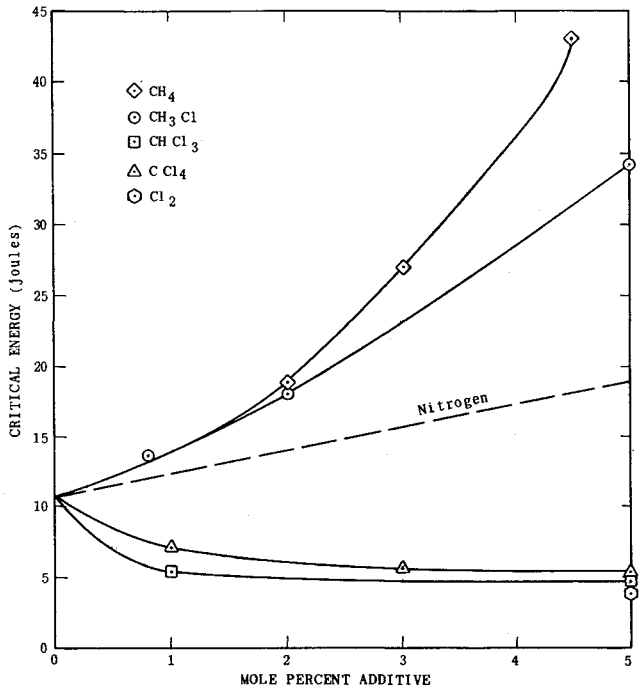

Fig. 4 Effect of chlorine and chlorine-substituted methanes, added to the mixture consisting of 62% H_2 and 38% O_2, on critical energy for initiation of spherical detonation.

for the pure hydrogen-oxygen mixture, depending on initiation energy, and up to 80 μsec for some mixtures containing additives. The corresponding transit time for a steady-state detonation wave in the hydrogen-oxygen mixture would be 36 μsec. This means that, for initiation energies much above the critical, the predetonation delay is only a few microseconds; for energies near the critical, it may be 40 to 50 μsec.

The critical initiation energy for the hydrogen-oxygen mixture without additives was found to be between 10.3 and 10.8 joules, in excellent agreement with the values of 10.5 to 11.0 joules reported by Litchfield.[10] The system is rather sensitive to dilution. The critical energy for detonation of the mixture increases approximately linearly with addition of nitrogen to 19 joules for 5 mole % of nitrogen. In Figs. 2–4, which show the results of tests with various additives, the effect of dilution by nitrogen is included for the sake of comparison.

A. Alkanes

The effect of addition of five saturated hydrocarbons to the hydrogen-oxygen mixture is shown in Fig. 2. The solid lines are drawn through the experimental points for methane and propane, since all the other data fall between these two curves. Although the divergence of the data in some cases is appreciably larger than the experimental scatter, the gross effects of the five additives on the critical energy are essentially similar.

B. Alkenes

The effect of five unsaturated hydrocarbons is shown in Fig. 3. The differences among these substances are very pronounced. While ethylene sensitizes the hydrogen-oxygen mixture, propylene, trans-butene-2, and iso-butene are excellent inhibitors of detonation. The effects of propylene and trans-butene-2 are the same within the experimental accuracy.

C. Chlorine and chlorine-substituted methanes

The effect of chlorine and chlorine-substituted methanes is shown in Fig. 4. Addition of 5% of chlorine resulted in the lowest critical energy found in this program. It is evident that the presence of bound chlorine also sensitizes the mixture.

D. Freons

Two totally halogenated hydrocarbons were tested, bromotrifluoromethane and 1,2-dibromotetrafluoroethane; the latter is known to be a fairly good inhibitor of laminar flames.[12] Both compounds have a sensitizing effect on initiation of detonation (see Table 1).

E. Miscellaneous additives

Pentacarbonyl iron, an excellent flame inhibitor,[11] was found to be also an efficient inhibitor of detonation, in a class with propylene and trans-butene-2 (see Fig. 3). On the other hand, tetramethyl lead, a well-known antiknock agent, has a distinct sensitizing effect. The effects of bromine, hydrogen bromide, methyl bromide, and water are only slight, not appreciably different from that of nitrogen. Methyl iodide was found to be a somewhat better inhibitor than methyl bromide, but poorer than methyl chloride. Di-tertiary butyl peroxide is a sensitizer. These data are collected in Table 1.

Discussion

The chemical systems discussed in this paper are similar to many systems studied in connection with the problems of flame inhibition, flammability limits, kinetics of chain reactions, explosion limits, and the like. However, the enormous initial temperatures arising from the explosion of the wire and the subsequent fairly high shock pressures, under which chemical reactions take place in the spherical detonation experiment, are so different from those encountered under milder conditions that the reaction mechanisms also must be expected to be different. A few points of similarity and contrast with the information obtained in other circumstances follow.

The finding that hydrocarbons inhibit the forming of detonation in hydrogen-oxygen mixtures parallels, in a general fashion, the results on inhibition of laminar hydrogen-air flames.[12] An exception is ethylene, which inhibits the flame and sensitizes the detonation. This difference can be accounted for perhaps by the fact that mixtures of ethylene and oxygen are extremely sensitive to detonation by exploding wires. Indeed, the critical energies for hydrogen-oxygen mixtures containing ethylene, shown in Fig. 3, are intermediate between the critical energy for the pure hydrogen-oxygen system and the reported value of 8.5 joules for the ethylene-oxygen system.[9] The mixtures of oxygen and alkanes, of course, are detonable also, but their critical energies are several times higher.[9]

Other qualitative points of agreement of tests in flames[11, 12] with the forementioned detonation data are the effects of chlorine, which was found to be a sensitizer in both instances, and of pentacarbonyl iron, which is an inhibitor in both

Table 1 Critical energies (joules) of H_2-O_2 mixtures with additives[a]

Mole percent additive	1	1.5	2	3	4	5
Bromotrifluoromethane	...	...	8.3	...	8.5	...
1,2-dibromotetrafluoroethane	...	...	6.6	...	8.1	...
Pentacarbonyl iron	21.8	...	36.0	...	...	...
Tetramethyl lead	...	...	7.4	9.5	...	...
Di-tertiary butyl peroxide	...	6.5	...	...	...	...
Bromine	...	...	...	...	...	16.3
Hydrogen bromide	...	...	...	10.9	...	18.4
Methyl bromide	...	...	...	15.3	...	16.4
Methyl iodide	...	...	...	...	...	23.6
Water	...	...	...	15.0	...	...

[a] Critical energy of the mixture without additives is $E_i = 10.5 \pm 0.3$ joules.

instances. On the other hand, the effects of totally halogenated compounds are discrepant; both chlorotrifluoromethane and dibromotetrafluoroethane inhibit flames but sensitize detonations.

The detonation inhibition results for hydrogen-oxygen systems do not correlate well with the flammability limit data for hydrogen-air systems. For instance, while methyl bromide is an excellent flammability suppressant,[15] it has very little effect on formation of detonation (see Table 1). The fact that methyl chloride is a more efficient detonation inhibitor than either methyl bromide or methyl iodide is also at variance with flame-inhibition experience.

Results with hydrocarbons allow some correlations to be made with reaction kinetics. The data in Fig. 4 show that the two compounds containing methyl radicals (CH_4 and CH_3Cl) inhibit the formation of detonation, whereas the other three promote it. Although this result may suggest inhibition by removal of chain carriers (H, O, OH) by alkyl radicals, tests with unsubstituted hydrocarbons offer the stronger evidence that the important step is interception of carriers by molecules and not by radicals. First, the data with di-tertiary butyl peroxide (see Table 1) show that a profusion of methyl radicals does not result necessarily in inhibition. Second, if capture by methyl radicals were an important step, one would expect larger alkyl radicals to be even more efficient; but data in Fig. 2 do not show large alkanes to be more effective detonation inhibitors than small ones.

It thus appears that the inhibition effect of hydrocarbons may be accounted for by the occurrence of the reaction $RH + X \rightarrow HX + R$, where R is a hydrocarbon radical and X a chain carrier. Chemical kinetic data[13, 14] show the reaction rates of oxygen atoms with transbutene-2, isobutene, and cis-butene-2 (in that order) to be very high; with butene-1 and propylene appreciably less; with ethylene much less; and with alkanes quite low. Fundamental considerations indicate that the same order of reactivity should be expected of reactions of other active species (e.g., hydrogen atoms) with hydrocarbon molecules. The order of inhibition effectiveness by hydrocarbons thus correlates rather well with the ease of removal of a hydrogen atom from the hydrocarbon molecule.

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Some Pressure-Drag Effects of Rounding the Leading Edges of Hypersonic Inlets

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Nomenclature

$C_{D,b}$ = round leading-edge drag coefficient
$C_{p,t,2}$ = total pressure coefficient back of a normal shock at M_∞
$C_{p,t,\beta}$ = total pressure coefficient back of a normal shock at Mach number, $M_\infty \cos\beta$
d/D_c = ratio of leading-edge diameter to capture area diameter
d/g = ratio of leading-edge diameter to gap of rectangular inlets
l = distance from inlet to outlet
M_∞ = freestream Mach number
β = sweep angle of a rectangular inlet
δ = outer-surface cone half-angle
θ = angle of a normal to the surface measured relative to the freestream direction
θ_j = value of θ at juncture of the round leading edge with the straight surface

STUDIES of the possible performance of external air-breathing engines require an estimation of the power-plant drag that must be subtracted from the computed internal-thrust forces. In this paper an axisymmetric power-plant is at first assumed with an outer surface of conical form terminating at an exit diameter larger than the inlet diameter. Charts for determining pressure drag and skin-friction drag for slender sharp-leading-edged bodies of this type were devised and are presented in Ref. 1.

In order to be realistic it must be admitted that at hypersonic Mach numbers the leading edge will be rounded to relieve stagnation-point heating. In the present paper, consideration is focused on pressure-drag effects on the rounded leading edge and the pressure-drag effects resulting from changes in pressure further back on the conical surface caused by rounding the leading edge. All computations are for a perfect gas with ratio of specific heats of 1.4.

Estimates were made of the external pressure-drag coefficients of selected ducted bodies at Mach numbers of 4, 12, and 15. The external pressure drag was considered to consist of the entire leading-edge pressure drag plus the pressure drag on an outer conical surface going from the leading edge back to the exit station. The drag coefficient was based on an inlet area bounded by the center-of-curvature line of the leading edges.

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