with six-degree-of-freedom numerical solutions for widely varying roll rates. The angle-of-attack expression is used to calculate the drag, and the drag in turn is used to obtain an expression for the body velocity. The approximate solution for the velocity is in good agreement with a six-degree-of-freedom numerical solution.

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# Ignition Catalysts for Furfuryl Alcohol —Red Fuming Nitric Acid Bipropellant

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### Introduction

THE hypergolicity of liquid propellants is a desirable characteristic because it eliminates the need for complex mechanical and electrical starting devices in rocket motors. It is not enough that the bipropellant be self-igniting; it is essential that it should have short ignition delay with smooth burning. This is necessary in order to prevent accumulation of dangerous quantities of unburned propellants in the combustion chamber. From this point of view, many investigations[1,2] have been made to discover catalysts which could reduce the ignition delay of hypergolic propellants and improve the ignitability. The importance of discovery of catalysts is quite well known; sometimes the ignition of nonhypergolic propellants has been accomplished in the presence of certain catalysts.[3–5]

With these points in view, studies have been carried out to discover catalysts which could reduce the ignition delay of furfuryl alcohol—red fuming nitric acid hypergolic bipropellant.

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### *Materials*

Red fuming nitric acid containing 16% water by volume was used as oxidant. Chemically pure furfuryl alcohol was used as such without any further purification. The following catalysts were used: a) soluble: potassium chromate, sodium nitroprusside, ferric chloride, zinc oxide, copper chromate, and magnesium powder; b) insoluble: ammonium metavanadate, sodium metavanadate, cuprous oxide, potassium dichromate, potassium ferrocyanide, cupric oxide, and potassium permanganate.

### *Measurement of ignition delay*

The ignition delay (I.D.) was measured by cup test experiments, as described earlier.[1] First the catalyst was added in red fuming nitric acid containing 16% water by volume. The purpose of diluting red fuming nitric acid with water was to increase the ignition delay of furfuryl alcohol and the red fuming nitric acid (RFNA) system, otherwise the effect of catalysts would not have become apparent because the ignition of furfuryl alcohol with concentrated RFNA is almost instantaneous. It may also be mentioned here that $NH_4VO_3$ and $Cu_2O$ which are known to be soluble catalysts[1] in RFNA, become insoluble in diluted red fuming nitric acid. Ignition delay was always measured by reacting 0.45 mliters of furfuryl alcohol and 0.60 mliters of the oxidant. The concentration of catalyst was 3 g in 100 $cm^3$ of RFNA. In certain cases, when the catalyst was insoluble in RFNA, the solution (RFNA + catalyst) was thoroughly shaken before use. The experiments were done at room temperature (28 ± 1°C).

### Results and Discussion

The experimental results are given in Tables 1 and 2. From a practical view point and for convenience, soluble catalysts are preferred in injection, hence greater emphasis was placed on discovering these catalysts. Out of the soluble catalysts tried, potassium chromate, sodium nitroprusside, ferric chloride, zinc oxide, and copper chromate have been found to reduce the ignition delay of furfuryl alcohol-RFNA bipropellant (Table 1). But potassium chromate and copper chromate are the most effective in reducing the ignition delay and in both these cases very vigorous, smooth and elongated flames were observed. Of all the insoluble catalysts studied, ammonium and sodium metavanadates, cuprous oxide, potassium dichromate, potassium ferrocyanide, cupric oxide, and potassium permanganate reduce the ignition delay (Table 2). But it is noteworthy that sodium metavanadate, potassium dichromate, potassium ferrocyanide, and potassium permanganate reduce the ignition delay enormously and in case of these catalysts, very vigorous flames were observed. It may be mentioned here that in case of $KMnO_4$ catalyst, the fresh solution is always to be used otherwise it would lose its activity. The cause of this behavior has already been investigated by Rastogi and co-workers.[5]

The chemical rate processes occurring either during ignition or during steady-state combustion are not understood well enough to provide a complete explanation for the role of catalysts during ignition. The search for a suitable catalyst

**Table 1 Average ignition delay in case of soluble catalysts**

| Catalyst | I.D., sec |
|---|---|
| None | 1.8 |
| Zinc oxide | 1.1 |
| Magnesium powder | 1.1 |
| Ferric chloride | 0.8 |
| Sodium nitroprusside | 0.7 |
| Potassium chromate | 0.4 |
| Copper chromate | 0.35 |

**Table 2 Average ignition delay in case of insoluble catalysts**

| Catalyst | I.D., sec |
|---|---|
| None | 1.8 |
| Cupric oxide | 1.1 |
| Cuprous oxide | 1.0 |
| Ammonium metavanadate | 0.9 |
| Sodium metavanadate | 0.5 |
| Potassium dichromate | 0.4 |
| Potassium permanganate | 0.3 |
| Potassium ferrocyanide | 0.25 |

can be facilitated if the mechanism of the reaction between the fuel and the oxidizer leading to ignition is known. If the intermediate stage which takes longer time can be indentified, then one may think of a suitable catalyst for accelerating it. With this aim, a detailed study of the mechanism of the reaction between furfuryl alcohol and RFNA is, therefore, in progress.

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# Effects of Polarization on Radiant Heat Interchange between Simply Arranged Surfaces


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### Nomenclature

$A$ = area
$B_{i-j}$ = absorption factor
$B_{e-j}$ = absorption factor for external incoherent radiation
$E$ = emitted energy flux
$I_b$ = intensity of blackbody radiation given by Planck's law
$N$ = number of reflections in the enclosure
$T$ = temperature
$\epsilon$ = emissivity
$\theta$ = angle between surface normal and ray
$\kappa$ = $\epsilon_p(\theta)/\epsilon(\theta)$
$\rho$ = reflectivity
$\sigma$ = Stefan-Boltzmann constant
$\Omega$ = solid angle

***Subscripts and superscripts***

$p,s$ = parallel and perpendicular planes of polarization, respectively
$*$ = polarized
1,2,3 = surfaces 1, 2, and 3

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### Introduction

THE effect of polarization is usually ignored in engineering calculations of radiant heat transfer. Edwards and Bevans[1] have, however, shown that the absorption of solar energy can be seriously in error if polarization is neglected, and Edwards and Tobin[2] have found that the transmittance of incoherent radiation through long passages is quite sensitive to polarization of radiation.

The purpose of this Note is to investigate the effect of polarization on the radiant heat transfer for some simple configurations of engineering interest. Three different geometrical configurations are considered, but for the sake of brevity, the problem is formulated only for configuration 1 (see Fig. 1). The plates are taken to be made of smooth isotropic materials of sufficient optical depth as to be opaque to nearly all the thermal radiation emitted by these bodies.

### Analysis

Consider radiant heat exchange between two isothermal bodies 1 and 2 (see Fig. 1, configuration 1), one at temperature $T_1$ and another at temperature $T_2$, due to their own emission as well as an external incident radiation. Since the general problem is linear it can be separated into two subproblems and the general solution obtained by superposition of the two subproblems.[3] It is assumed in the analysis that the geometric optics theory is valid for radiant heat exchange and that the surfaces are separated by a nonabsorbing, nonscattering medium having a constant index of refraction. To reduce the number of parameters the radiation characteristics of the surfaces are assumed to be identical.

The energy emitted from the elementary area per unit area and time into the solid angle $d\Omega$ around the direction $\theta$ is

$$dE = dE_p + dE_s = \tfrac{1}{2}[\epsilon_p(\theta) + \epsilon_s(\theta)]I_b \cos\theta d\Omega \qquad (1)$$

Since the plane of emission and incidence for this energy is the same and the two surfaces are identical, the fraction of this energy absorbed[4] at surface 1, denoted by $dB_{d1-1}$, can be written as

$$dB_{d1-1} = \rho(\theta)[1 - \rho^{2N_1}(\theta)]/[1 + \rho(\theta)] \qquad (2)$$

Note that for a given geometry the number of interreflections $N_1$ at surface 1 depends not only on the polar angle $\theta$ but

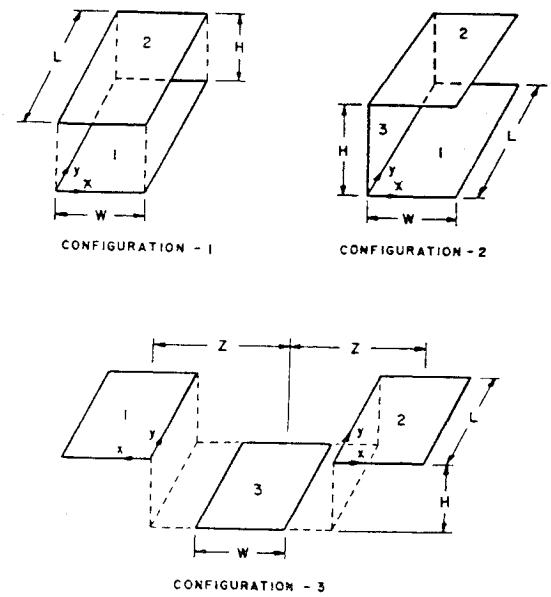


**Fig. 1 Configurations analyzed; all surfaces specular.**