Effect of adding water to the propellant of a DME arcjet thruster

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Abstract: We proposed and demonstrated that DME could be used as a substitute arcjet propellant. Trial experiments, however, suffered from unstable behavior accompanied by discharge instabilities. We suspected that carbon deposits contaminating the anode nozzle after operation were providing the source of the instabilities. Based on an idea that the carbon could be eliminated via reactions with high-temperature water vapor known as the steam reforming mechanism, we conducted a theoretical study and experimental work adding water to the main DME propellant to ascertain if the above concept is achievable.

I. Introduction

Taking advantage of the physical properties of dimethyl-ether (DME), such as reasonably high vapor pressure, low freezing temperature, and no toxicity,[1] we proposed the use of DME as a propellant for arcjets and started trial experimental work. The results showed that DME could act as a substitute arcjet propellant with a reasonably good specific impulse at the sub-N level.[2, 3] The plenum chamber pressure and thrust, however, suffered from unstable behavior accompanied by discharge instabilities. The anode nozzle after operation was contaminated with carbon deposits, which we suspected could be the source of the instability. To protect the nozzle from the accumulation of carbon deposits, we determined that the carbon could be eliminated by an oxidizing reaction, e.g., reactions with high-temperature water vapor. In this study, first the possibility of the effectiveness of this concept was examined theoretically and then experiments were conducted to ascertain whether the above concept is actionable.

II. Background Issue to be Solved

An estimated comparison of the performances of hydrazine (N_2H_4) and dimethyl-ether (DME) as propellants of arcjets is shown in Fig. 1. The calculation was conducted with CEA[4] in the range of up to 50 MJ/kg for the specific power input, *Psp*, which corresponds, for example, to a power input of 1 kW with a propellant mass flow of 20 mg/s. This appears to suggest that the performance with DME is close to equivalent to that with hydrazine, taking the advantages of DME mentioned in the introduction into consideration. This was our main motivation for starting trial experiments with DME.

The results with the DME propellant, however, yielded unstable thrusts both in magnitude and direction accompanying by the anode nozzle clogging up, as shown in Fig. 2. Photos of an original anode nozzle and one after use are shown in Fig. 3. The operation conditions were *Pin* = 2 kW for the power input and $\dot{m}$ = 60 mg/s for the mass flow rate.

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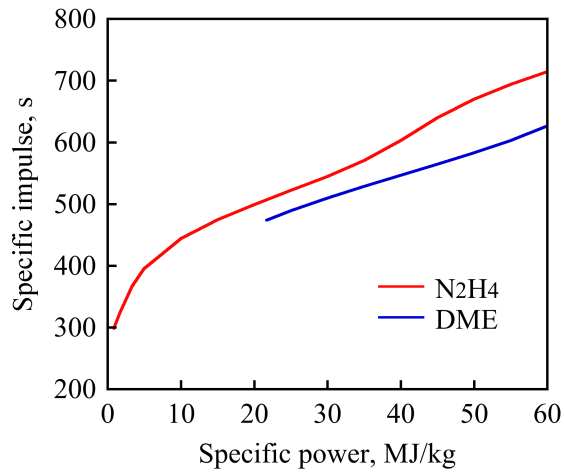


Figure 1. Performance comparison between arcjets with hydrazine and DME propellant.

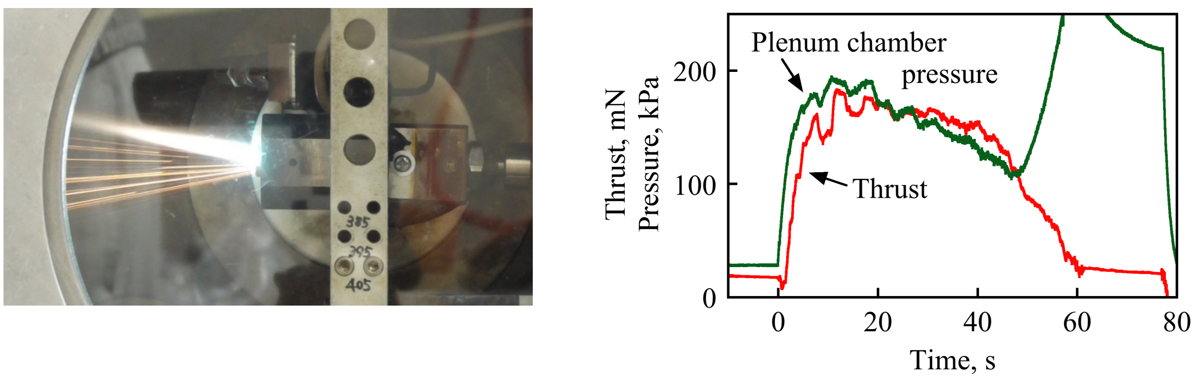


Figure 2. Photo and thrust behavior during operation in the case with a pure DME propellant.

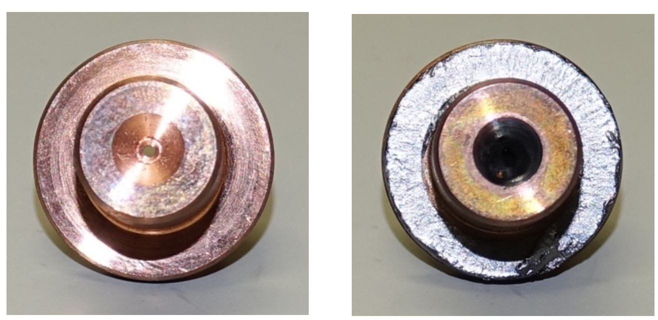


Figure 3. Original anode nozzle (left) and one after use (right) with a pure DME propellant.

III. Proposed Method

The substance causing the clogging is thought to be carbon, which is expected due to the carbon contained in the DME molecules when dissolved. Therefore, we hypothesized that carbon elimination could be achieved using an oxidizing reaction with carbon. In particular, the reaction between carbon and water at high temperature was tried by adding a small amount of water to the DME propellant.

Figure 4 shows the theoretical tendency of the carbon amount estimated in the exhaust emitted in the case where water is supplied to the main DME propellant. This figure indicates the removal of carbon with the addition of water. The performance as the specific impulse versus the specific power was evaluated for different water content ratios and is shown in Fig. 5.

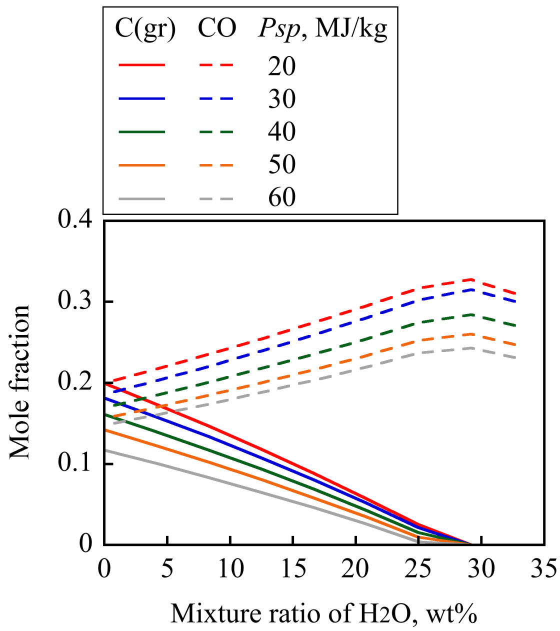


Figure 4. Carbon amount estimated in the exhaust with varying water content.

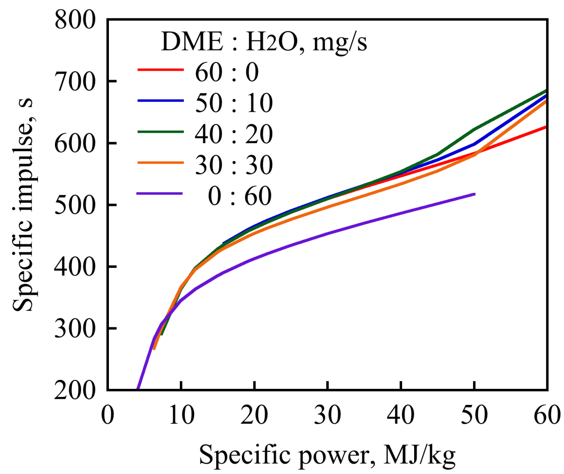


Figure 5. *Isp* evaluated with varying water content.

Based on the indicated behavior, we conducted arcjet firing tests. Figure 6 shows a photograph of the test thruster, which is equipped with an inlet port to supply water to the main DME propellant. The supply amount and ratio of DME to water were adjusted using a mass flow controller (3660, KOFLOC) for the DME propellant and an in-house modified controller for the water (a modified NTFD-3S-3, Surpass Industry).

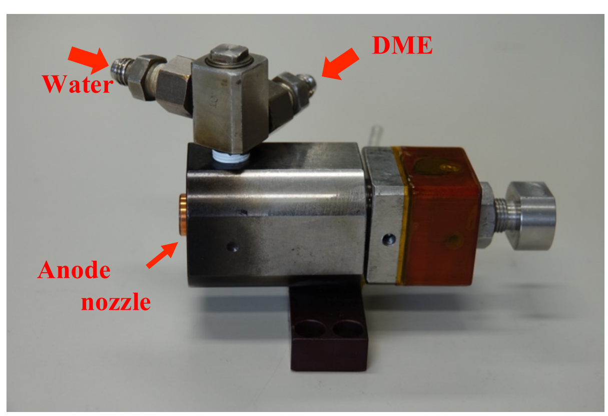
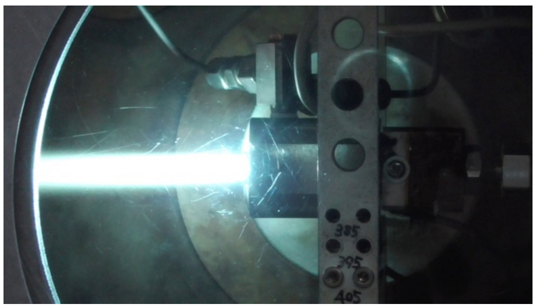


Figure 6. The test thruster.

IV. Experimental Results and Discussion

A photo and the thrust behavior in a case with water added to the DME propellant is shown in Fig. 7, where it appears that both the magnitude and direction of the thrust are improved. The operation conditions are Pin = 2 kW for the power input and $\dot{m}$ = 60 mg/s for the mass flow rate. Figure 8 shows photos of the anode nozzle to compare the cases operated with the pure DME propellant and those operated with the addition of water. It appears that the water can effectively reduce the accumulation of carbon emitted as a DME resolution substance. The reaction mechanism is given in the following.



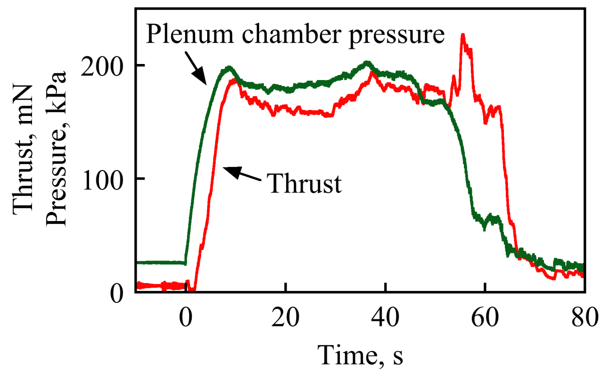


Figure 7. Photo and thrust behavior during operation in the case with the H_2O-supplemented DME propellant.

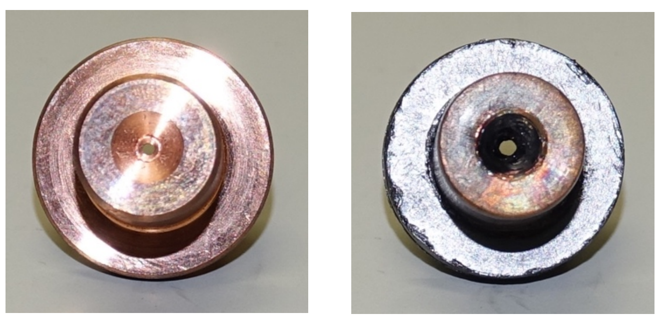


Figure 8. Anode nozzle before use (left) and after use (right) with the addition of water.

The graph shown in Fig. 9 shows the approximated mole fractions of C, CO, CO_2, and H_2 at various temperatures, where the reaction between C(gr) and H_2O,

$$C(gr) + H_2O \rightarrow CO + H_2, \qquad (1)$$

becomes more dominant as the temperature increases over approximately 1500 K, and the reaction

$$C(gr) + 2H_2O \rightarrow CO_2 + 2H_2 \qquad (2)$$

tends to occur as the temperature decreases. Reactions (1) and (2) are the main mechanisms converting C(gr) into CO or CO_2 known as the steam reforming reaction such as in the production of reducing gases[5], and the results support the theory that the addition of water can effectively diminish soot formation.

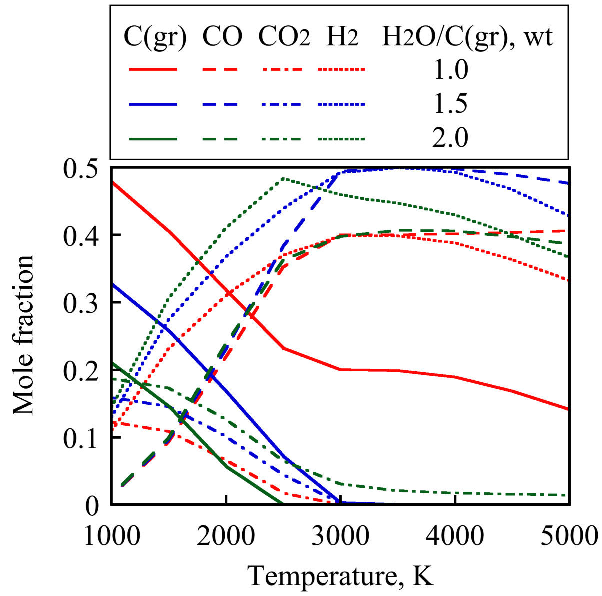


Figure 9. Fractions of C, CO, CO_2, and H_2 calculated at various temperatures.

V. Summary

The following is a summary of this study.

1) Carbon is emitted during the resolving process when DME is used as a propellant for arcjets, and this carbon then deteriorates the performance.
2) Carbon emission appears to be lowered by the addition of water via an oxidizing reaction with carbon at high temperatures.
3) Nozzle clogging was acceptably suppressed by the proposed method following the anticipated mechanism.

References

[1]Japan DME forum, *DME handbook*, Ohmsha, Tokyo, 2006, Chaps. 2, [in Japanese].

[2]Kakami, A., Yokote, J., Ebara, I., and Tachibana, T., "Application of Dimethyl Ether to Arcjet Thruster as Propellant," *Vacuum*, Vol. 83, No. 1, 2009, pp. 77-81.

[3]Kakami, A., Beppu, S., Maiguma, M., and Tachibana, T., "Performance of Dimethyl Ether Arcjet Thruster and Its Dependence on Electrode Configurations," *Journal of Propulsion and Power*, Vol. 28, No. 3, 2012, pp. 603-608.

[4]Gordon, S., and McBride, B. J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications," NASA RP-1311, 1994.

[5]Yamamoto, Y., Kakami, A., and Tachibana, T., "Conversion of Utmost Rich Mixtures to Reducing Gases by Plasma-Assisted Reaction," *Frontier of Applied Plasma Technology*, Vol. 5, No. 1, 2012, pp. 42-45.