Feasibility of Increasing Specific Impulse of Supersonic Nozzles by Lithium Condensation*

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Theme

A POSSIBLE way of increasing the specific impulse of electrothermal thrusters without incurring excessive material temperatures is by the addition of heat to the supersonic stream. Leon and Mickelsen[1] conclude that of the several possible methods of supersonic heat addition the most attractive appears to be the partial condensation of a propellant vapor in the supersonic stream, and that lithium is the best propellant due to its high heat of vaporization and low-molecular weight. The analysis of Leon and Mickelsen predicts that substantial condensation of lithium vapor will take place in nozzles of large area ratio and small divergence angle, and that specific impulses of greater than 500 sec will be achieved at plenum temperatures below 2000°K. The present experimental work studies the possibility of heat addition due to partial condensation of lithium vapor propellant in the supersonic portion of a nozzle. Performance gains of the magnitude predicted by the theory of Ref. 1 were not observed.

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The experimental apparatus is shown schematically in Fig. 1. The thruster consists of a re-entrant nozzle mounted at the end of a lithium heat pipe,[2] which acts as an isothermal plenum for temperatures greater than 1200°K. Nozzle area ratio (A/A^*) was varied from 20 to 400 and nozzle half angle from 2.5° to 5.0°. The small nozzle divergence was selected in an attempt to enhance condensation effects. The nozzle throat area was 0.02 cm² for all cases. Heat to vaporize the propellant was supplied from an RF induction heater of 20 kw capacity. The range of stagnation temperatures was from 1275°K to 1710°K, corresponding to plenum pressures from 0.05 to 2 atm. The thruster was mounted on a thrust balance consisting of a beam with strain gages mounted on it to measure beam deflection. The balance was covered with a water-cooled oil bath to minimize thermal drift of the gages. Calibration of the thrust balance was done with calibrated weights to an accuracy of ±.5 g. The lithium vapor in the exhaust beam was condensed on the walls of a water-cooled calorimeter located above the thruster. The power deposited in the calorimeter was obtained by measuring the water flow rate and temperature rise.

The purpose of the experiment was to measure the specific impulse (I_{sp}) of the thruster over a temperature range 1200°K–1800°K. This can be done by measuring the thrust and mass flow rate through the nozzle using

$$I_{sp} = T/\dot{m} \tag{1}$$

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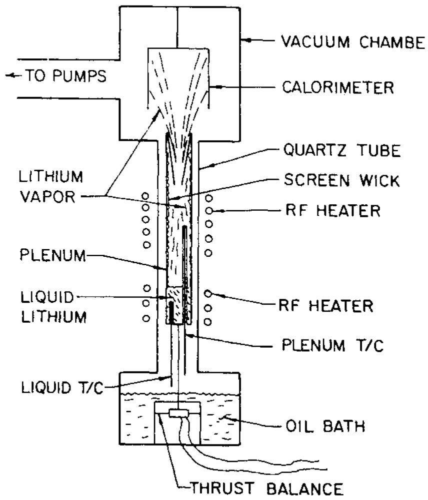

Fig. 1 Schematic of thruster assembly.

where T = rocket thrust (g), and $\dot{m}$ = propellant mass flow (g/sec). The force on the thrust balance at any moment is composed of: 1) the tare weight of the empty thruster assembly, 2) the weight of propellant remaining in the plenum, and 3) the force generated by the vapor flow through the nozzle. The rocket thrust (T) at any moment is thus

$$T = F(t) - F_o + \int_{t_o}^{t} \dot{m} dt \tag{2}$$

where $F(t)$ = total measured force on the thrust balance at time (t), F_o = initial load (thruster + propellant) at time (t_o), and $\dot{m}$ = propellant mass flow rate. The lithium mass flow rate is determined by two independent measurements: 1) the slope of $F(t)$ vs t at a constant plenum temperature; and 2) the total calorimeter power (corrected for thermal radiation) divided by the total enthalpy in the lithium vapor at the plenum temperature. The two methods of determining mass flow rate agreed well with each other and agreed well with the mass flow determined by measuring the thruster weight before and after the run. For the purpose of determining thrust and specific impulse, the slope of the $F(t)$ vs t curve was used to determine the mass flow rate.

The experimentally determined values of specific impulse as a function of plenum temperature for two nozzle configurations is shown in Fig. 2. The triangular symbols are for a nozzle having an area ratio, A/A^*, of 300 and a divergence half angle of 4°. The hexagonal symbols are for a nozzle having an $A/A^* = 400$ and a divergence half angle of 5°. It is seen that the difference in nozzle configuration had essentially no effect on the measured specific impulse. For comparison the calculated value for ideal isentropic flow of a monatomic vapor is also shown (curve labeled "monatomic"). An exact comparison with the theory of Ref. 1 is not possible since the plenum stagnation pressures, p_0, were four to eight times higher than those used by Leon for his calculations. Since the

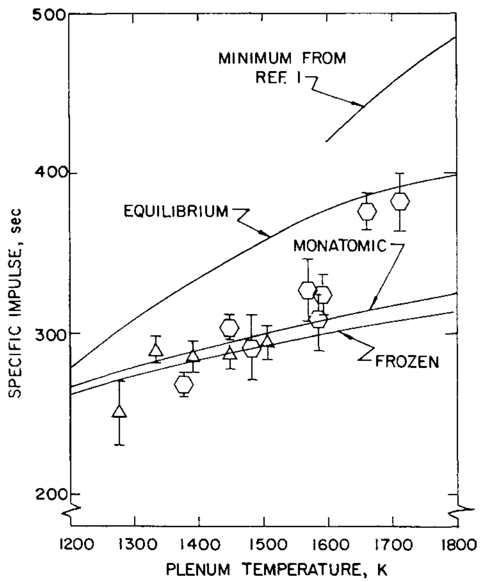

Fig. 2 Comparison of experimental and calculated specific impulse.

theory predicts an increase in I_{sp} with an increase in p_o, theoretical values lie above the line labeled "minimum from Ref. 1." For example the theory of Ref. 1 predicts that at a plenum stagnation temperature, T_o, of 1700°K the I_{sp} increases from 382 sec for $p_o = 0.06$ atm, to 413 sec for $p_o = 0.12$ atm, and to 458 sec for $p_o = 0.42$ atm. For the present experiment $p_o = 2$ atm at $T_o = 1710$°K.

In an attempt to explain the experimental result that I_{sp} approaching the values predicted by Leon and Mickelsen were not observed, the role of molecular association, i.e., formation of Li_2 was considered. To investigate the effect of dimers on the nozzle flow the appropriate differential equations for equilibrium molecular flow were derived and integrated numerically. For this flow the vapor composition ($Li + Li_2$) is always in equilibrium. Condensation is not considered but the heat addition due to the formation of Li_2 is included. Ionization and excitation effects were considered, but were found to be negligible. Viscous effects were not explicitly considered in the calculation. The results of this calculation are shown as the curve labeled "equilibrium" in Fig. 2. Calculations for frozen molecular flow with a dimer concentration equal to that in the plenum, and therefore representing the nozzle performance without either molecular association (dimerization) or condensation, were also performed. These calculations utilized the usual relations for isentropic flow with the vapor molecular weight and ratio of specific heats appropriately adjusted for the presence of Li_2 (curve labeled "frozen" in Fig. 2).

The experimental points, in general, fall between the specific impulse calculated for frozen molecular flow and for equilibrium molecular flow. The experiment approaches the theoretical performance of equilibrium flow (reacting but noncondensing) at the highest plenum temperatures and pressures. It is proposed that the experimental results can in part be explained by considering the role of molecular association, i.e., formation of Li_2 during the expansion. The mole fraction of dimer increases throughout the expansion. The specific impulse increases above the frozen flow value because of the energy release attendant to dimer formation. The quantitative results demonstrate that the heat release accompanying molecular formation significantly retards condensation by reducing the supersaturation ratio of the expanding flow. For example the supersaturation ratio at the nozzle throat is reduced an order of magnitude from the values for frozen and monatomic flows. At the lower plenum temperatures and pressures the measured I_{sp} is significantly lower than the equilibrium value; being close to the frozen flow values. This reduction in the performance may be associated with a reduction of the reaction rates at the lower temperatures and/or viscous effects. At the low Reynolds numbers (small scale and low plenum pressures), small divergence angles, and large expansion ratios at which the experiments were conducted, viscous effects can substantially reduce performance. Such viscous effects are also undoubtedly acting to help reduce the I_{sp} below the values predicted by Ref. 1.

In conclusion, the realization of significant improvement in the specific impulse of lithium vapor emerging from a converging-diverging nozzle because of volume condensation as predicted by the theory of Leon and Mickelsen has not been demonstrated in the present experiments. Molecular formation and energy release significantly delay the onset and rate of condensation. Extremely large nozzle area ratios are necessary if the latent heat due to condensation is to be recovered. Viscous effects further reduce performance. Even in equilibrium condensing flow, high temperatures and pressures are necessary to cause the rate of condensation to proceed efficiently in fast flowing, expanding, streams. These considerations suggest that significant enhancement of specific impulse by condensation in alkali metal systems is unlikely. The low over-all efficiency which accompanies flow without condensation and fabrication difficulties for high-temperature, high-pressure operation, further reduce the technical merit of the concept. Furthermore, the inclusion of dimer formation effects and viscous effects, both neglected by Leon and Mickelsen, will be necessary to properly calculate the performance of such nozzle flows.

References

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