Additives for Heat-Transfer Reduction in the Propellant Combinations N_2O_4-MMH and N_2O_4—A-50

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In an earlier paper,[1] adding silicone to the fuel was discussed for the propellant combinations IRFNA-UDMH and HDA-UDMH—for Agena thrust sizes. In both regeneratively cooled applications, heat transfer was significantly reduced—more than 30%—by the dynamic coating formed by the SiO_2 deposited on the engine wall. This effort has been expanded by experimenting with silicone fuel additives in the N_2O_4-MMH and N_2O_4—A-50 propellant systems. Tests were conducted at thrust sizes from 500 to 6000 lb at 100–200 psi chamber pressure and 16,000 lb at 500 psi chamber pressure. These rocket engines used a variety of coolant barrier types and cooling techniques, i.e., radiation or water cooled. All tests indicated heat-transfer reductions of more than 30%.

Nomenclature

h_1 = over-all thermal conductance from gas driving temperature to coolant in absence of silica, BTU/ft² hr°F
h_2 = effective silica conductance = k/x, BTU/ft² hr°F
k = thermal conductivity, BTU/ft² hr°F/in.
x = effective thickness of silica deposit, in.
$(Q/A)_1$ = measured heat flux in absence of fuel silicone additive, BTU/in.² sec
$(Q/A)_2$ = measured heat flux in presence of fuel silicone additive, BTU/in.² sec
U = over-all thermal conductance, BTU/ft² hr°F
ρ = barrier flow/total flow

I. Introduction

IN the late 1940's, General Electric's Project Hermes evaluated silanes and other silicone compounds like GE 81077 as ethyl alcohol additives to reduce the heat flux in LOX-alcohol rocket engines. In the process of combustion, these soluble additives formed a dynamic, i.e., continuously replenishing coating on the engine surface which significantly reduced the heat flux to the regeneratively cooled engines. It was determined that the coating consisted mostly of silicone dioxide. Heat-transfer reductions greater than 30% could be obtained with silicone fuel additives of less than 2% by weight.

At Bell Aerospace Co. these investigations have been extended to propellant combinations using such oxidizers as inhibited red fuming nitric acid, high-density nitric acid and N_2O_4 and such fuels as UDMH, MMH and A-50. Some of the HDA/UDMH effort is reported in a previously cited paper.[1] This paper presents data obtained with the propellant combinations N_2O_4—A-50 and N_2O_4-MMH.

II. Discussion

The purpose of the evaluation was to assess the effectiveness of several fuel-soluble silicone additives as a function of coolant barrier film type, cooling technique, and thrust size. To do this, four different hardware configurations were tested under similar operating conditions—with and without silicone additive. These were: 1) A radiation-cooled, coated columbium chamber, with a 3.4-in. diam and a 1.605-in. throat diameter. This configuration incorporates a fuel vortex barrier and yields about 640 lb thrust (at $\epsilon = 40$) at 175 psia chamber pressure. Reference 2 gives the pertinent description of the hardware configuration. 2) A chamber configuration, consisting of an 8-in. diam ablative chamber and a water-cooled nozzle. The throat diameter was 5.478 in. The injector consisted of 84 triplets and 93 doublets. This unit yields about 5000 lb thrust (at $\epsilon = 40$) at 175 psia chamber pressure. The coolant barrier is formed by low mixture ratio (~ 1.0) combustion doublets. Figure 1 shows the configuration. 3) A configuration dimensionally identical to the one just described except that the ablative chamber was replaced by a heavy stainless chamber incorporating a separately fed fuel vortex barrier. Figure 2 shows this configuration. 4) A configuration comprised of an Agena injector, modified for use with the propellant combination N_2O_4-MMH (S/N 9), an uncooled chamber and a water-cooled nozzle. The nozzle area ratio is about 2.2. The coolant barrier is provided by combustion doublets, operating at a ratio of 0.75 : 1. The nominal engine thrust is about 16,000 lb. Figure 3 shows the hardware assembly. The test experience for each of these four configurations will now be discussed.

A. Radiation-Cooled Columbium Engine

The use of radiation-cooled columbium chambers allowed the application of pyroscanners to obtain a thermal profile of the engine continuously during the test. This permits a direct measurement of temperature uniformity and maximum wall temperature as well as the definition of the wall temperature

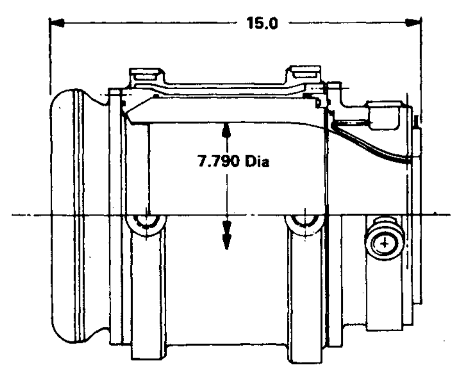

Fig. 1 Ablative chamber and water-cooled nozzle assembly.

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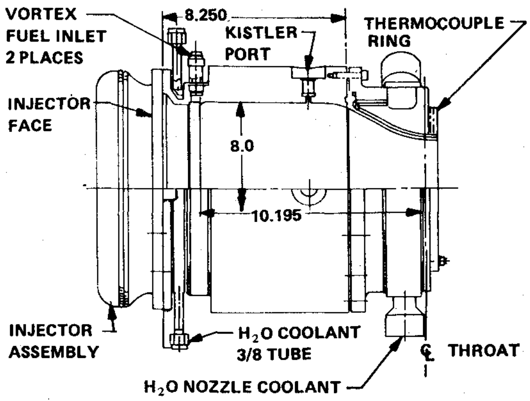

Fig. 2 Fuel vortex injector—water-cooled nozzle assembly.

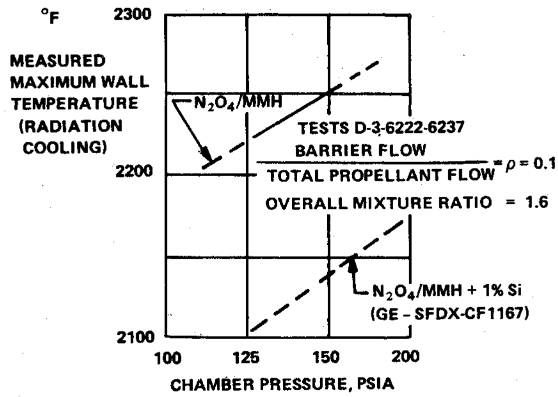

Fig. 4 Measured maximum wall temperature vs chamber pressure

transient through equilibrium. From the latter data, it is possible to compute the effective gas-side heat-transfer coefficients and wall-driving temperature by assuming a one-dimensional radial heat flow. Since the heat balance requires that at any instant the heat input to the wall from the combustion gas is equal to the sensible heat absorbed by the wall plus the radiant heat lost to the environment, a plot of heat flux, Q/A, vs wall temperature yields a line, the slope of which is the value of the "effective" gas-side heat-transfer coefficient and the intercept of which at $Q/A = 0$ represents the local gas driving temperature. Since the wall temperature is measured up to equilibrium condition for a radiation cooled engine, the extrapolation of the data to obtain adiabatic wall temperature is small, i.e., less than 300°F. Therefore, this method of computing adiabatic wall temperature from the available experimental data is considered fairly accurate.

Test series were conducted with N_2O_4-MMH and N_2O_4-MMH plus 1% silicone (GE SFDX-CF 1167). Figure 4 is a plot of the measured maximum wall temperature with and without the fuel additive. It is indicated that the additive has reduced the maximum wall temperature by about 100°F. From the "effective" gas-side heat-transfer coefficients computed at the maximum temperature location by the method previously described, the resistance contribution of the silica layer can be computed by using the equation

$$U = (1/h_1 + x/k)^{-1} \qquad (1)$$

U is the effective gas-side heat-transfer coefficient in the presence of the additive while h_1 is the effective gas-side heat-transfer coefficient for the neat propellants. The value of k/x at chamber pressure = 125 psia was determined to be about 600 BTU/ft^2 hr°F. It should be emphasized that the method of calculation makes this value subject to considerable error; however, it should be sufficiently accurate to provide an approximation of the silica thickness. Assuming a thermal conductivity for SiO_2 of 4.3 BTU/ft^2 hr°F/in., the effective local thickness of the dynamic coating at the maximum temperature point would be about 0.007 in. Evaluation of coatings removed after test has shown that the deposit is almost pure SiO_2. The value for the conductivity was assumed on the basis of data for a foamed SiO_2 presented in Ref. 3. The thickness of coatings observed after the test appear to be in the range of values previously computed. Since the local coatings spall off and then replenish themselves continuously, any calculation of coating thickness represents some mean value over the replenishment period.

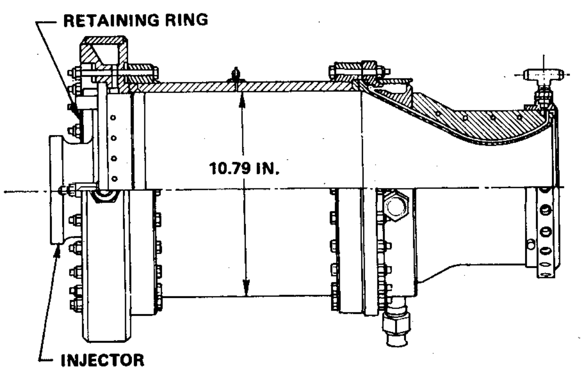

Fig. 3 Chamber assembly.

Of course, we can question whether the observed wall temperature reduction, when the fuel additive is used, is due solely to the thermal resistance introduced by a silica layer. If it is, then the adiabatic wall temperature (at $Q/A = 0$) should be the same whether the additive is used or not. Thermocouple measurement of the wall temperature of an insulated chamber as well as computation of the adiabatic wall temperature ($Q/A = 0$) by the one-dimensional equation described previously seem to confirm that the dynamic coating acts as a thermal resistance, i.e., there is little or no change in the adiabatic wall temperature. No significant performance change was observed between the silicone additive and neat fuel tests.

B. 8-in.-diam Ablative Chamber-Combustion Doublet Barrier

In these test series, the propellant combination was N_2O_4—A-50. The silicone additive was 1% GE SFDX-CF 1167. The tests were conducted over a range in chamber pressure from 115 to 175 psia. The average nozzle heat flux was computed from the measurements of water flow rate and the inlet and outlet temperatures. Table 1 summarizes the data. It is apparent that the silicone fuel additive reduced the over-all nozzle heat flux by more than 40%.

C. 8-in.-diam Stainless Chamber-Fuel Vortex Barrier

This hardware was almost identical, from a configuration standpoint, with that of the series just described except for the use of the fuel vortex barrier. N_2O_4—A-50 and the same silicone fuel additive were used in one test series—and N_2O_4-MMH and fuel silicone additive GE 104-2489 in another. These data are tabulated in Table 2. Note that both silicone fuel additives provide significant reduction in overall heat flux.

D. Modified Agena Configuration

The propellant used was N_2O_4-MMH and the fuel silicone additive used was GE-SFDX. These data are summarized in Table 3. It is apparent that a significant reduction in heat flux was obtained.

If the over-all conductance, in the absence of silicone additive, from the combustion gas to the water is designated

Table 1 Data summary

Test number	Chamber pressure (psia)	Over-all mixture ratio	c* fps	Silicone additive	Average nozzle heat flux (BTU/in.^{2} sec)
D4-4262	133	1.90	Unreliable data	Yes	1.62
D4-4263	126	1.86	5540	Yes	1.29
D4-4264	159	1.67	5590	Yes	1.65
D4-4265	172	1.53	5655	Yes	1.34
D4-4266	116	1.81	5520	No	2.33
D4-4267	175	1.55	5600	No	3.19

Table 2 Test data for fuel vortex—cooled configurations

Test number	Chamber pressure (psia)	Fuel	Over-all mixture ratio	Fuel barrier percentage	c* fps	Additive	Average nozzle heat flux BTU/in.^{2} sec
D4-4275	177	A-50	1.58	8.2	5360	None	2.07
D4-4276	178	A-50	1.58	8.1	5375	None	2.38
D4-4277	177	A-50	1.55	10.1	5320	None	2.15
D4-4278	175	A-50	1.68	6.0	5425	None	2.66
D4-4279	174	A-50	1.77	3.7	5465	None	2.93
D4-4280	178	A-50	1.62	8.1	5370	0.9% SFDX	1.37
D4-4281	176	A-50	1.72	5.9	5425	0.9% SFDX	1.32
D4-4282	174	A-50	1.81	3.9	5465	0.9% SFDX	1.27
D4-4283	175	MMH	1.60	8.5	5390	None	1.65
D4-4284	174	MMH	1.70	6.3	5424	None	1.98
D4-4285	173	MMH	1.83	4.0	5469	None	2.15
D4-4286	179	MMH	1.60	8.0	5384	0.7% 104-2489	1.30
D4-4287	180	MMH	1.61	5.8	5451	0.7% 104-2489	1.28
D4-4288	181	MMH	1.61	4.0	5494	0.7% 104-2489	1.25

Table 3 Modified Agena configuration data

Test number	Chamber pressure (psia)	Over-all mixture ratio	c* fps	% Silicone	Average nozzle flux (BTU/in^2. sec)
1	499	1.90	5530	0.0	5.71
2	489	2.07	5470	0.0	5.69
3	501	1.90	5555	0.6	3.07
4	501	1.70	5580	0.6	2.81
5	500	2.09	5495	0.6	3.14
6	500	1.89	5540	1.3	2.66
7	496	1.70	5565	1.8	2.47

as h_1, and h_2 is the effective silicone conductance, then

$$[Q/A]_2/[Q/A]_1 = h_2/(h_2 + h_1) \tag{2}$$

For an assumed gas barrier driving temperature of 3200°F, we can write

$$h_2 = \frac{\dfrac{[Q/A]_2}{3200}}{1 - \dfrac{[Q/A]_2}{[Q/A]_1}}(518400) \tag{3}$$

Comparing tests 1, 3, and 6

$$h_2(\text{Si} = 0.6\%) = 1080 \text{ BTU/ft}^2 \text{ hr°F}$$

$$h_2(\text{Si} = 1.3\%) = 809 \text{ BTU/ft}^2 \text{ hr°F}$$

Comparing tests 2 and 5

$$h_2(\text{Si} = 0.6\%) = 1135 \text{ BTU/ft}^2 \text{ hr°F}$$

Taking again a thermal conductivity of 4.3 BTU/ft^2 hr°F/in. for SiO_2, the effective average thickness about 0.004 to 0.005 in.

Conclusion

Silicone fuel additives effectively reduce the heat flux in rocket engines using N_2O_4 and A-50 or MMH. Both combustion doublets and fuel vortex barriers have demonstrated the capability to facilitate the formation of a dynamic coating. The effectiveness of the dynamic coating is produced by the high thermal resistance introduced by the silica deposit.

References

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[3] "Thermophysical Properties of Thermal Insulating Materials," A.F.M.L. Technical Documentary Report ML-TDR-64-5, April 1964, Wright Patterson Air Force Base, Ohio, p. 202.