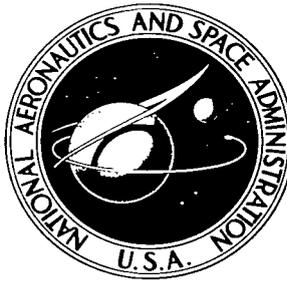


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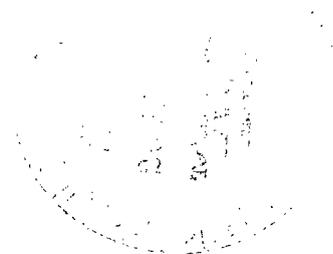


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GASEOUS-FILM COOLING OF A ROCKET MOTOR WITH INJECTION NEAR THE THROAT

by James G. Lucas and Richard L. Golladay

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SUMMARY

Gaseous-film cooling of an adiabatic wall was studied in a small JP-4 - gaseous-oxygen rocket motor. The nitrogen coolant was injected tangentially to the wall through an annular slot at an axial location slightly upstream of the nozzle throat in the area of rapidly accelerating hot-gas flow. Data were obtained with two different slot heights. The adiabatic wall temperature measurements downstream of the coolant injection slot indicated that the film coolant was effective over the full length of the nozzle. The wall temperature data were correlated for approximately 100 slot heights downstream of the coolant injection slot by a modified Hatch-Papell equation. The modifications required were a reduction of the constant in the Hatch-Papell equation from 0.04 to 0, the use of local hot-gas static temperature rather than recovery temperatures as the driving temperature, and a change in the term hgL , which is the heat-transfer coefficient times the circumference of the engine, from a constant value at the coolant injection location to an integrated average between the injection location and the individual downstream data-measuring stations.

Over the lower portion of the coolant flow range studied, anomalous behavior of the adiabatic wall temperature pattern was observed with one slot height. The wall temperatures tended to be much lower than expected, which would seem to indicate that coolant flow optimization might be possible in a design application. At present, however, the reasons for the existence of this effect are unknown.

The lip of the tangential coolant injection slot was a critical component in the design because of thermal expansion. With the physical restraints against radially outward lip movement necessitated by the need to maintain the preset slot height, the thermal expansion causes circumferential compressive stresses above the yield point with consequent lip shrinkage and slot-height growth after the termination of firing. The heavy compressive stresses can also cause buckling of the lip between its radial supports. In an actual flight application of gaseous-film cooling, the slot lip would require careful design to avoid the effects of thermal expansion and to minimize the disturbing effects on coolant flow of both the lip thickness and the lip supports.

INTRODUCTION

Among the many high-temperature fields of interest for which advanced cooling concepts are being studied, rocket motors of various types appear to present some of the most difficult problems for the designer. All the various types of rocket motors (liquid, hybrid, solid, nuclear, etc.) have their characteristic cooling problems. For example, in a liquid-propellant rocket motor, as the combustion pressure is raised the usual regenerative cooling scheme eventually becomes inadequate. Reference 1, in an investigation of such cooling problems, concludes that with conventional materials the upper limit in chamber pressure for regenerative cooling of a liquid-hydrogen - liquid-oxygen rocket motor is about 2000 pounds per square inch absolute, and at 5000 pounds per square inch absolute the regenerative coolant could absorb only about 40 percent of the maximum heat flux. This reference also indicates that gaseous-film cooling not only appears quite attractive theoretically in the regimes of interest to augment the regenerative cooling, but also appears feasible from the fabrication standpoint. Similar conclusions can be reached in favor of film cooling when analyzing the need for cooling augmentation in various other types of advanced rocket motors.

Film cooling is a method of insulating the surface to be protected from the rapidly flowing hot propellant gases by interposing a thin film of a cooling liquid or gas along the surface, flowing cocurrently with the hot gases, to absorb and carry away all or a portion of the total convective heat flux from the hot gases. A gaseous-film coolant could be injected as a gas, or it could be injected as a liquid film coolant and used as a gas-phase coolant after evaporation. For a designer to use gaseous-film cooling in an engine, he must have an expression which relates the downstream wall temperature distribution to coolant injection variables and hot-gas heat-transfer variables. Much work has been done (e. g., ref. 2) to develop and refine such correlations in the low-temperature, low-heat-flux regimes. Such information in the high-temperature, high-heat-flux regimes is in notably short supply in the literature. The analytical and experimental efforts found in references 3 and 4 yielded a semiempirical correlation of reasonable accuracy for an adiabatic flat plate with gas temperatures up to about 2000^o R and velocities up to about 1000 feet per second. The experimental results of reference 5 indicated that the Hatch-Papell correlation of references 3 and 4 could be applied to a small rocket motor with hot-gas temperatures in the 5000^o R range with reasonable accuracy with coolant injection in the cylindrical portion of the combustion chamber. Reference 6 indicates that the Hatch-Papell equation can be used, with suitable modification, for correlating the nonadiabatic equilibrium wall temperatures in a small rocket motor utilizing both gaseous-film cooling and external convective cooling.

The present experimental investigation, conducted at Lewis Research Center as a continuation of that of reference 5, is intended to provide useful information on the

application of the Hatch-Papell equation with nitrogen coolant injection occurring in the convergent portion of the nozzle in a region of high velocity and high acceleration of the hot gases. This area is of interest to designers who may be considering the use of gaseous-film cooling in the high-heat-flux region surrounding the nozzle throat, possibly to aid a regenerative cooling system with an otherwise impossible heat load. However, the present experimental investigation uses an adiabatic wall rather than a convectively cooled wall in an effort to add only one new variable at a time to the previous work, and thus, hopefully, to isolate the effects of this one variable.

The nitrogen gas used as a coolant in this investigation is a poor coolant when judged by the ratio of its mass flow to the propellant mass flow. As discussed in reference 5, a coolant of lower molecular weight would be used in a flight application, and the resulting reduction in mass flow ratio would be of the order of the reduction in molecular weight of the coolant. Nitrogen gas was chosen for the present investigation because of its availability, low cost, and nonreactivity with the products of combustion of the propellants.

EXPERIMENTAL APPARATUS AND PROCEDURE

The rocket motor used for this investigation was designed to burn JP-4 fuel and gaseous oxygen at combustion pressures up to 500 pounds per square inch absolute with a corresponding maximum thrust of 3700 pounds. For the present investigation, the combustion pressure was set at a constant value of 60 pounds per square inch absolute,

and a stoichiometric mixture ratio was maintained during all firings. This engine was designed to permit studies of wall heat transfer through the nozzle, and all other components were therefore designed conservatively and ruggedly to provide maximum reliability. The propellant injector used had 40 concentric orifice elements (oxygen around fuel) arranged in three circular rows (fig. 1). Nozzle and chamber heat-transfer measurements had indicated that this injector gave a reasonably uniform circumferential distribution of wall heat flux. The combustion chamber was water cooled and had an internal coating of zirconium oxide to help lower the heat flux to the chamber wall. Downstream of this chamber there could be fitted the appropriate

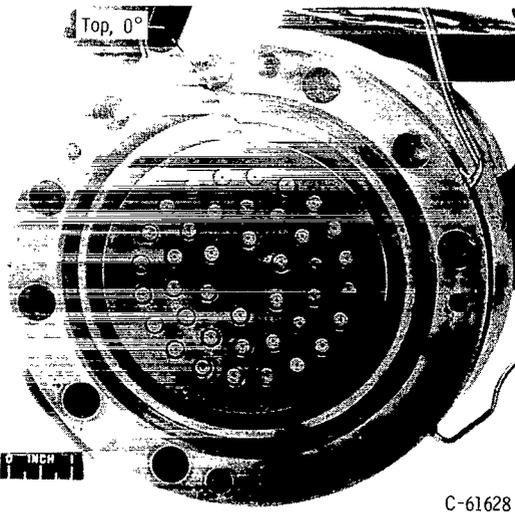


Figure 1. - Propellant injector.

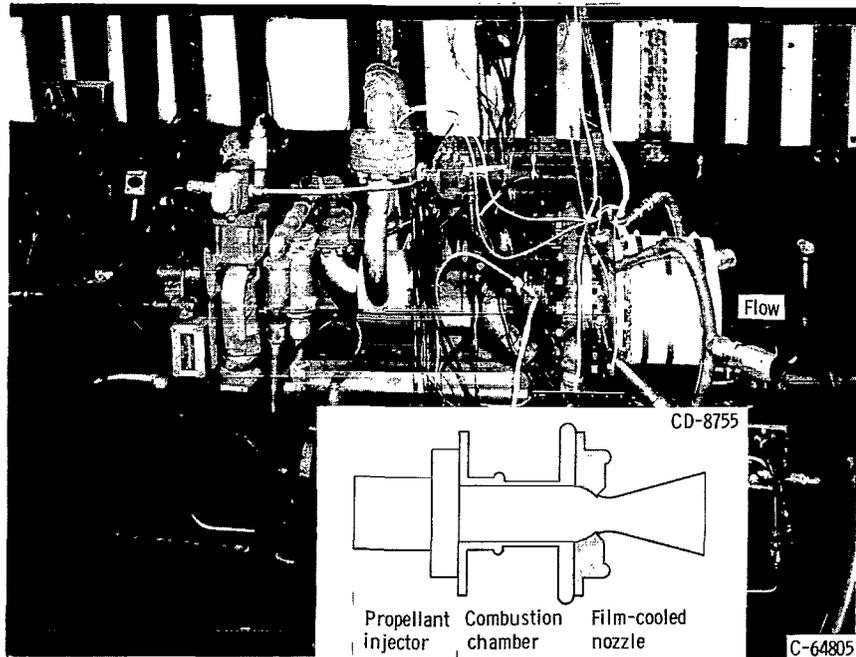


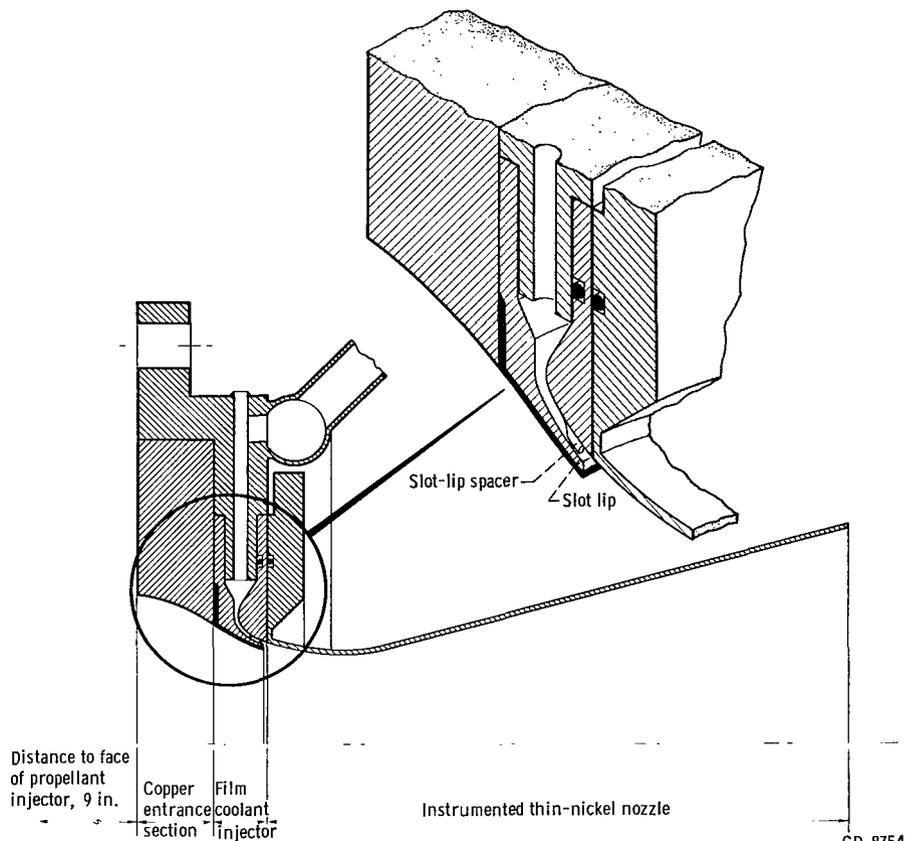
Figure 2. - Rocket motor installed in test facility.

item of research hardware: heat-sink or gaseous-film-cooled spoolpiece or nozzle as desired.

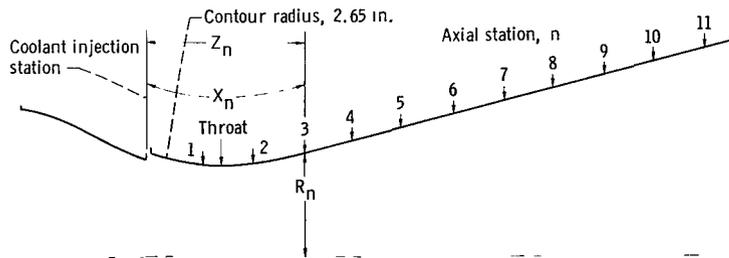
This rocket motor was fired in a 10-foot-diameter altitude tank in which ambient pressure down to 1.4 pounds per square inch absolute could be maintained along with a flow of air up to 40 pounds per second past the motor to dilute, cool, and carry off the products of combustion. For each firing, the tank ambient pressure was set at a value very close to the nozzle-discharge static pressure of the combustion gases to minimize any effect of over- or under-expansion of these gases. A general view of the rocket motor and its associated hardware installed in the altitude tank is shown in figure 2.

The propellant flows to the motor were governed by a calibrated electronic control system that would vary the flows to maintain a preset mixture ratio and combustion chamber pressure. This control varied the oxygen fire-valve opening in response to a combustion chamber pressure signal, and then similarly varied the fuel flow to maintain the proper ratio of the two flows. In addition, this control would open the propellant fire-valve slowly according to a preset ramp at the start of firing to provide a fairly gentle start with minimum overshoot of chamber pressure. An automatic program timer was used to maintain the proper timing and sequence of the various functions involved in the firing, such as purges before and after firing, torch ignition, activation of the automatic flow control, etc. In addition, various safety controls were provided to prevent or terminate firing if certain conditions of temperature, coolant flow, etc. did not exist.

A cross section of the test nozzle for the present investigation is shown in figure 3.



(a) Cross section of test-nozzle assembly and detail of coolant injection slot.



Axial station, n	Surface distance, X_n , in.	Axial distance, Z_n , in.	Radius, R_n , in.	Thermocouple location					
				Row A	Row B	Row C	Row D	Row E	Row F
Coolant injector	0	0	1.551						
1	.838	.805	1.336	✓		✓		✓	✓
Throat	1.115	1.096	1.325						
2	1.588	1.534	1.378	✓		✓		✓	✓
3	2.338	2.260	1.563	✓		✓		✓	✓
4	3.088	2.984	1.755	✓	✓	✓	✓	✓	✓
5	3.838	3.709	1.946	✓		✓	✓	✓	✓
6	4.588	4.433	2.137	✓		✓		✓	✓
7	5.338	5.158	2.327	✓		✓		✓	✓
8	6.088	5.882	2.519	✓		✓		✓	✓
9	6.838	6.606	2.710	✓		✓		✓	✓
10	7.588	7.331	2.902	✓		✓		✓	✓
11	8.338	8.056	3.121	✓		✓		✓	✓

(b) Nozzle thermocouple locations.
Figure 3. - Details of test hardware.

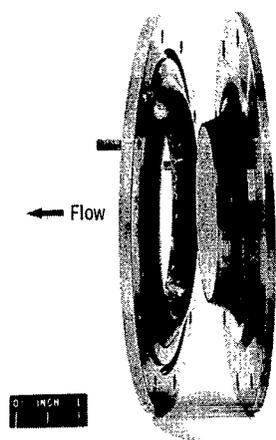
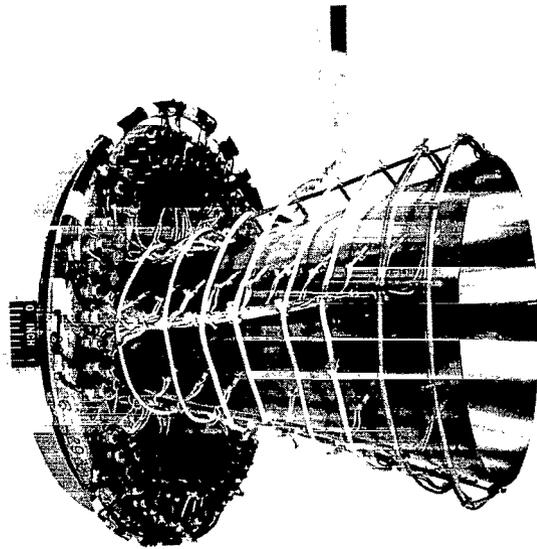


Figure 4. - Coolant injector elements.

The entrance section of the nozzle is a copper piece that forms part of the convergent contour of the nozzle and acts as a heat sink whose capacity is more than sufficient for the expected firing durations. Downstream of this copper piece is the film-coolant injector assembly, shown as a skewed view of a cross section in figure 3, whose basic elements are shown by the photograph in figure 4. The outer ring of this assembly forms the outer surface of the annular injection slot and has on this surface 30 raised spacers equal in height to the desired slot height. These spacers prevent the inner ring of the slot assembly, the slot lip, from thermally expanding radially outward and consequently closing the coolant slot with obviously disastrous results. These slot-lip supports were 0.040

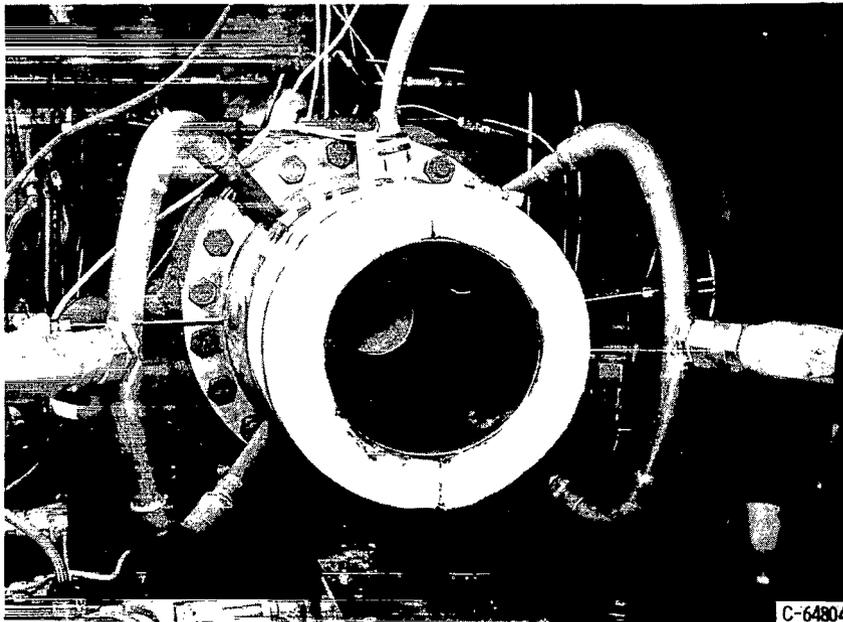
and 0.045 inch in height for the two phases of the present investigation. In circumferential width, the spacers measured about 0.025 inch at the end in contact with the slot lip, and the distance between them circumferentially was about 0.32 inch. With the fillets at the bases of the lip-supporting spacers, the blockage of flow area in the film-coolant slot amounted to approximately 15 percent. The surface of the slot lip that was exposed to the hot combustion gases was coated with zirconium oxide, flame-sprayed to a thickness of about 0.010 inch, to help insulate and protect the lip from the hot gases. Total lip thickness including the zirconium oxide coating was about 0.07 inch. The pressure-regulated, filtered nitrogen coolant gas was supplied to the slot at ambient temperature from a bottle farm through 20 equally spaced radial holes in the manifold assembly that discharged into an annular plenum immediately upstream of the slot. This system of gas supply to the slot had been shown in a previous phase of this program to provide a circumferentially uniform coolant efflux from the slot.

The film-cooled portion of the nozzle (fig. 5) starts at a point 1 inch upstream of the throat position measured along the axis. This essentially arbitrary location was chosen to place the film-coolant slot at, or slightly upstream of, the point of maximum heat flux in the nozzle. The contoured nozzle is spun of low-carbon nickel, nominally 0.060 inch thick, and is bolted to the coolant manifold and slot assembly by a stainless-steel flange to which it is welded. This weld is of minimum practical area to minimize heat conduction out of the thin nozzle wall, thereby causing minimum distortion of the axial distribution of measured wall temperatures. Instrumentation to measure the equilibrium or adiabatic wall temperature distribution along and around the thin nozzle consisted of platinum - platinum-13-percent-rhodium thermocouples spot-welded to the outside of the nozzle as shown on figure 5(a). The data thermocouples were placed in three axial rows,



C-64663

(a) Uninsulated nozzle showing spot-welded surface thermocouples.



C-64804

(b) Nozzle insulated and installed on rocket motor.

Figure 5. - Cooled thin-walled nozzle.

equispaced circumferentially, at 3/4-inch spacings as measured along the inner contour of the nozzle. At each axial station, the three thermocouple readings about the circumference were averaged in the calculation procedure to minimize the effects of any circumferential distortions of heat flux, coolant flow, etc., on the resulting data correlation and analysis. In addition to these readings, an additional three temperature measurements were made at the axial measuring station 3 inches downstream of the coolant injection point, giving six temperature measurements equispaced circumferentially at this station. These additional measurements aided in determining the presence or absence of circumferential distortions of wall temperatures.

The instrumented thin-wall portion of the nozzle was insulated on the outside with $\frac{1}{2}$ to 3 inches of glass-fiber matting that was covered with a high-temperature plaster shell as shown in figure 5(b). This insulation was necessary to prevent convective heat loss from the thin nozzle wall to air moving past the motor, which would result in lowered, nonadiabatic wall temperature measurements.

Propellant flows were measured with calibrated venturis, and the nitrogen coolant flow was measured with a calibrated orifice plate. The temperature of the coolant gas was measured in the annular plenum between the slot elements, shown in figure 4, about 1 inch upstream of the coolant slot outlet. The values of the various items of data for these measurements, as well as others such as combustion chamber pressure, altitude-tank ambient pressure, and all of the wall temperatures, were recorded by an automatic digital potentiometer on magnetic tape. Initially the data acquisition rate was 37.5 bits per second, but midway through the program this rate was changed to 18.75 bits per second to effect an improvement in the operational reliability of the digital potentiometer. This change had no effect on the value of the data obtained. A high-speed automatic computer converted and reduced the data to the desired form.

ANALYTICAL PROCEDURE

The Hatch-Papell equation for gaseous-film cooling, as presented in references 3 and 4, is given by

$$\ln \eta = \ln \frac{T_g - T_w}{T_g - T_c} = - \left(\frac{hgLX}{\dot{w}_c c_{p,c}} - K \right) \left(\frac{SV_g}{\alpha_c} \right)^{1/8} f \left(\frac{V_g}{V_c} \right) + \ln \cos 0.8 \beta_{\text{eff}}$$

where β_{eff} is in radians,

$$f\left(\frac{V_g}{V_c}\right) = 1 + 0.4 \tan^{-1}\left(\frac{V_g}{V_c} - 1\right) \quad \text{for } \frac{V_g}{V_c} \geq 1.0$$

and

$$f\left(\frac{V_g}{V_c}\right) = \left(\frac{V_c}{V_g}\right)^{1.5} \left[\left(\frac{V_c}{V_g}\right) - 1\right] \quad \text{for } \frac{V_g}{V_c} \leq 1.0$$

(Symbols are defined in appendix A.) Under the experimental conditions of the investigation in reference 3, the value of K was 0.04.

The basic correlating equation was derived for the case of cocurrent flows in a constant-area duct with no axial variation of hot-gas properties and velocity and with convection as the sole mechanism of heat transfer. Obviously, the nozzle of a rocket motor does not meet these specifications, although reference 5 indicated that the correlation could be used with reasonable accuracy in the convergent and throat portions of the nozzle with injection before the convergence and with an averaged heat-transfer coefficient; it was considered fortuitous that the simple equation did correlate the nozzle data, and in view of the more severe variations of flow and heat-transfer conditions represented by the present experiments, it was expected that some changes would be required in the Hatch-Papell equation to correlate the present data.

For the present data, with the hot-gas velocity always greater than the coolant velocity, $f(V_g/V_c)$ for $(V_g/V_c) \leq 1$ may be ignored, as may the term for the injection angle correction with the present situation of tangential injection.

Hot-gas properties were determined by a computer program (ref. 7) with equilibrium composition assumed for the combustion products. With the help of these properties, the hot-gas velocity for use in the correlation was calculated from the conditions existing at the downstream end of the coolant injection slot lip and was assumed to be constant at 2450 feet per second through the entire range of coolant flows. This assumption was made in view of the very small range of propellant flow rate and the difficulty in determining the exact diameter of the slot lip during a particular firing. The correlation is relatively insensitive to small changes in the hot-gas velocity, so the assumption of a constant value seems justified. Calculation of the coolant velocity is not as direct or as accurate. The method used entailed division of the measured coolant flow rate by the product of the coolant density and the injection slot area (neglecting the blockage caused by the lip spacers, which assumes that the coolant gas spreads out uniformly around the circumference). The coolant density was calculated from the measured coolant temperature in the slot T_c and the calculated hot-gas static pressure at the coolant injection station

(46.7 psia). Coolant velocities calculated in this manner ranged from slightly below to slightly above sonic velocity. The values are at least consistent among themselves, and the correlation equation is not overly sensitive to the actual value. For example, if the highest calculated velocity from the present data was reduced by 24 percent to the approximate local sonic value, the correlation parameter would be increased by only 9.9 percent. This method of calculating the coolant velocity is identical to that of reference 5, which permits direct comparison of the results.

The values of coolant specific heat and thermal conductivity (used in calculating the coolant thermal diffusivity α_c) were obtained from reference 8 evaluated at conditions in the annular plenum immediately upstream of the injection slot. Because of the small range of these conditions, it was practical to use constant values for these two parameters throughout the program. The values selected were 0.252 Btu per pound per $^{\circ}\text{R}$ for specific heat and 4.08×10^{-6} Btu per foot per second per $^{\circ}\text{R}$ for thermal conductivity.

TABLE I. - HOT-GAS STATIC TEMPERATURES THROUGH THE NOZZLE

Axial station	Hot-gas static temperature, T_g , $^{\circ}\text{R}$
1	5780
2	5580
3	5375
4	5210
5	5135
6	5040
7	4960
8	4892
9	4830
10	4775
11	4727

The hot-gas temperature T_g used in the correlation equation should properly be the adiabatic wall temperature without film cooling, or approximately the hot-gas total temperature as used in reference 5. For the present data, however, the correlation is better if the local hot-gas static temperatures are used as T_g , as shown in appendix B. The values of hot-gas static temperature were obtained from the computer program; they are theoretical values with no correction for combustion inefficiency. These hot-gas static temperatures are shown in table I for each of the wall temperature measuring stations as shown in figure 3(b) (p. 5).

The manner in which the hot-gas heat-transfer coefficient h_g and cooled path width L are used in the correlation is developed and discussed in appendix B. The method selected uses an integrated average of $h_g L$ measured from the coolant injection station to each of the axial measuring stations. The original data obtained from this investigation and used in the present correlation are found in table II.

TABLE II. - DATA FROM GASEOUS-NITROGEN FILM-COOLED NOZZLE

Slot height, S, in.	Coolant flow, w_c , lb/sec	Propel- lent flow, w_g , lb/sec	Chamber pressure, P_c , psia	Coolant tempera- ture, T_c , $^{\circ}R$	Wall temperature (average of three readings around circumference), T_w , $^{\circ}R$											Average of six readings, $T_{w,4}$, $^{\circ}R$
					$T_{w,1}$	$T_{w,2}$	$T_{w,3}$	$T_{w,4}$	$T_{w,5}$	$T_{w,6}$	$T_{w,7}$	$T_{w,8}$	$T_{w,9}$	$T_{w,10}$	$T_{w,11}$	
0.045	1.030	1.798	60.64	550	849	1196	1402	1499	1552	1580	1601	1599	1587	1548	1503	1494
	.951	1.880	61.50	556	899	1379	1622	1707	1757	1779	1791	1784	1766	1736	1685	1700
	.850	1.792	60.82	563	933	1418	1678	1788	1852	1874	1884	1872	1854	1824	1776	1799
	.796	1.828	61.47	550	913	1429	1697	1815	1879	1899	1912	1899	1880	1846	1801	1865
	.727	1.844	60.59	548	988	1411	1636	1746	1814	1844	1858	1848	1823	1777	1716	1768
	.711	1.814	60.35	542	977	1331	1525	1643	1721	1771	1799	1805	1796	1766	1719	1642
	.698	1.839	59.69	548	968	1342	1558	1672	1748	1788	1806	1806	1789	1751	1698	1669
	.665	1.902	58.67	521	1071	1538	1769	1885	1960	1996	2016	2009	1985	1941	1883	1859
	.633	1.875	60.89	558	1170	1672	1892	2001	2070	2101	2114	2108	2078	2035	1974	1992
	.624	1.906	59.72	518	1225	1692	1900	2007	2075	2102	2109	2095	2060	2008	1934	2041
	.596	1.771	58.48	517	1219	1697	1915	2038	2116	2154	2167	2164	2137	2096	2026	2038
0.040	0.813	1.838	59.56	529	1030	1453	1664	1759	1828	1871	1891	1897	1878	1837	1773	1737
	.749	1.838	60.13	548	1067	1536	1761	1868	1943	1988	2007	2006	1982	1931	1861	1855
	^a .749	1.838	60.13	548	1075	1581	1820	1931	2007	2054	2077	2085	2069	2019	1944	1905
	.701	1.861	59.85	542	1298	1747	1919	1999	2056	2084	2089	2081	2058	2007	1928	1971
	.692	1.818	59.57	548	1220	1669	1848	1932	1986	2012	2017	2014	1992	1954	1896	1921
	.674	1.871	59.03	539	1115	1629	1859	1962	2031	2064	2073	2063	2030	1979	1923	1951
	.652	1.811	58.67	528	1196	1592	1782	1886	1962	2008	2027	2022	1987	1950	1885	1899
	.652	1.886	59.95	530	1671	2024	2144	2221	2274	2294	2289	2263	2227	2161	2077	2189
	.649	1.930	62.37	551	1426	1915	2104	2203	2252	2271	2266	2241	2204	2150	2065	2176
	.627	1.837	59.52	528	1368	1828	2010	2109	2181	2212	2216	2193	2151	2090	2022	2090
	.625	1.828	59.35	574	1065	1688	1986	2111	2169	2186	2182	2160	2125	2075	2010	2092
	.613	1.950	60.51	535	1504	1878	2000	2072	2124	2149	2148	2135	2104	2050	1986	2084
	.600	1.898	60.18	554	1245	1795	2018	2127	2195	2226	2230	2119	2189	2145	2069	2139

^aData obtained after 78 seconds using the same conditions as the line above.

RESULTS AND DISCUSSION

Accuracy of Measured Equilibrium Wall Temperatures

Inasmuch as the wall temperature data to be used with the correlating equation must be equilibrium values, it was necessary to determine the duration of engine firing that would yield essentially these equilibrium values without being impractically or dangerously long. In addition, it was necessary to determine whether or not a sufficient degree of circumferential uniformity existed in the wall temperature values to justify the use of circumferential averages of the equilibrium wall temperatures obtained from the selected thermocouple placements.

During one run, the engine was allowed to fire for approximately 80 seconds. The circumferentially averaged wall temperature readings at the film coolant flow of 0.749 pound per second and the coolant injection slot height of 0.040 inch are plotted in figure 6 against axial distance downstream of the film coolant-injection slot after five different time intervals from the start of firing. The times shown are only approximate averages, inasmuch as the data for each curve were taken over a finite length of time. The full length of the nozzle was cooled far below hot-gas temperature, and the wall temperature accomplished most of its rise within the first 46 seconds. For this reason, and to lessen the exposure time of the rocket motor to the hazards of firing, the remainder of the firings were terminated after approximately 46 to 50 seconds of operation. To emphasize the nearness of the 46-second wall temperatures to equilibrium values, sample values of the circumferentially averaged wall temperature readings obtained at axial station 6 for three separate firings at different coolant flows are plotted against time from the start of firing in figure 7. These three curves have, by 46 seconds, reached values that can reasonably be used as equilibrium values, the terminal slopes of the curves being only about 0.7 to 1.6 degrees per second.

To determine whether or not the average of three wall temperature measurements at each axial station represented a reasonably true circumferential average, temperatures were measured during each firing at six equispaced circumferential locations at axial station 4. The temperature measurements at the end of firing indicated that maximum circumferential variations of $\pm 100^{\circ}$ to 150° R existed for most of the firings. The only apparent regular pattern of circumferential temperature distortion noted was a tendency toward low readings at the 180° (bottom) location, which was attributed to a defective thermocouple. The locations of the three thermocouples at each station that yielded wall temperatures used in the correlation equation were at 0° , 120° , and 240° , so the occasional error in wall temperature at 180° would not affect them. These three thermocouples at each station yielded temperature averages that appeared to represent a true circumferential average with reasonable accuracy.

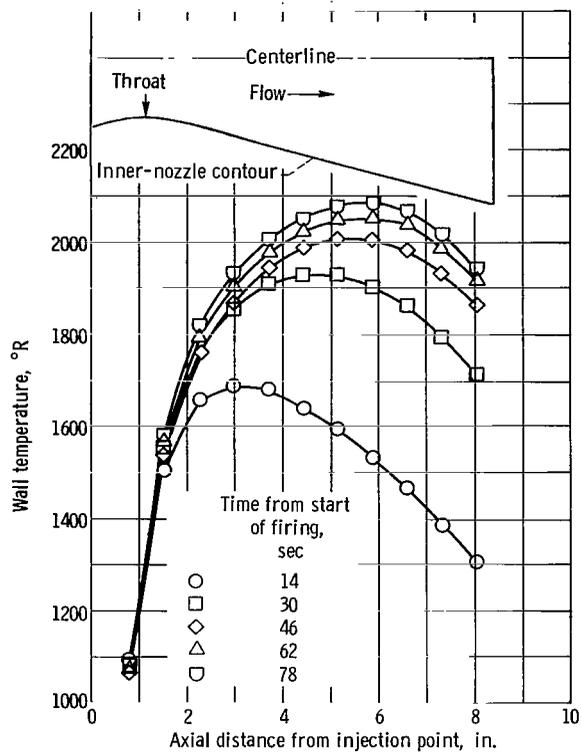


Figure 6. - Axial wall temperature distributions at several times after start of firing. Slot height, 0.040 inch; coolant flow, 0.749 pound per second.

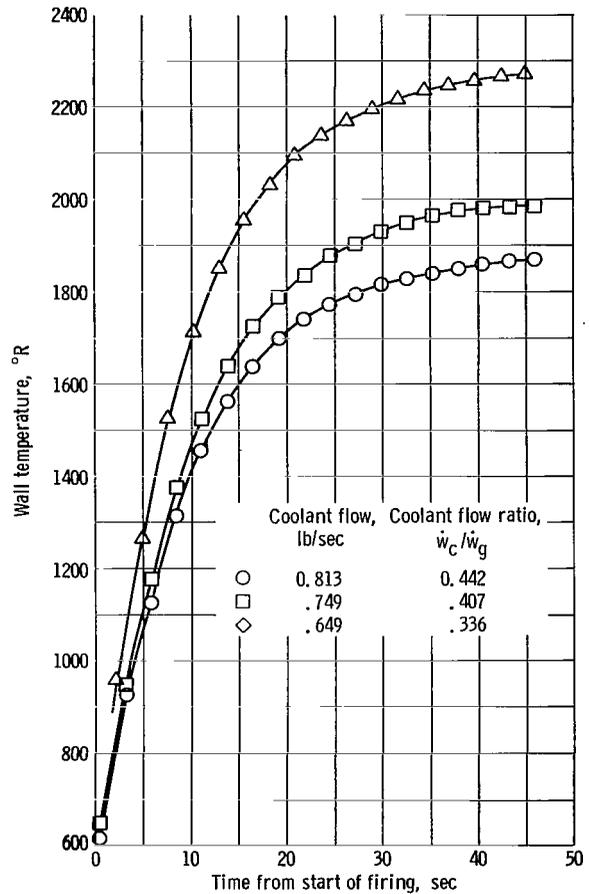
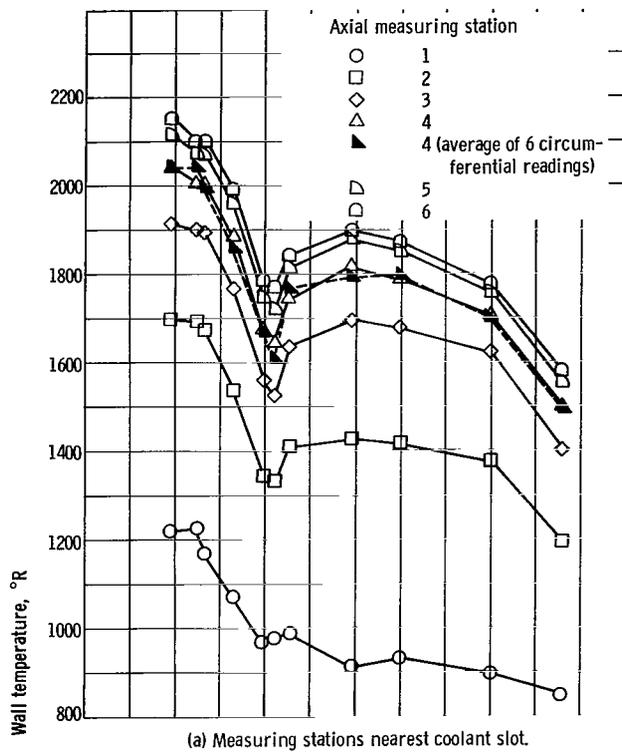


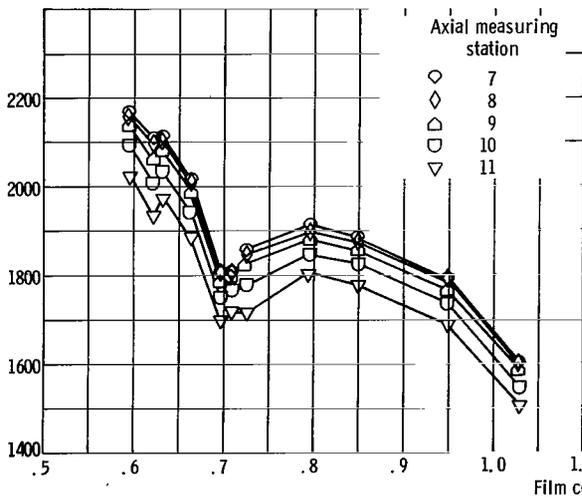
Figure 7. - Sample variations of wall temperature with time at axial station 6. Slot height, 0.040 inch.

Trends of Measured Wall Temperature with Variations of Coolant Flow and Slot Height

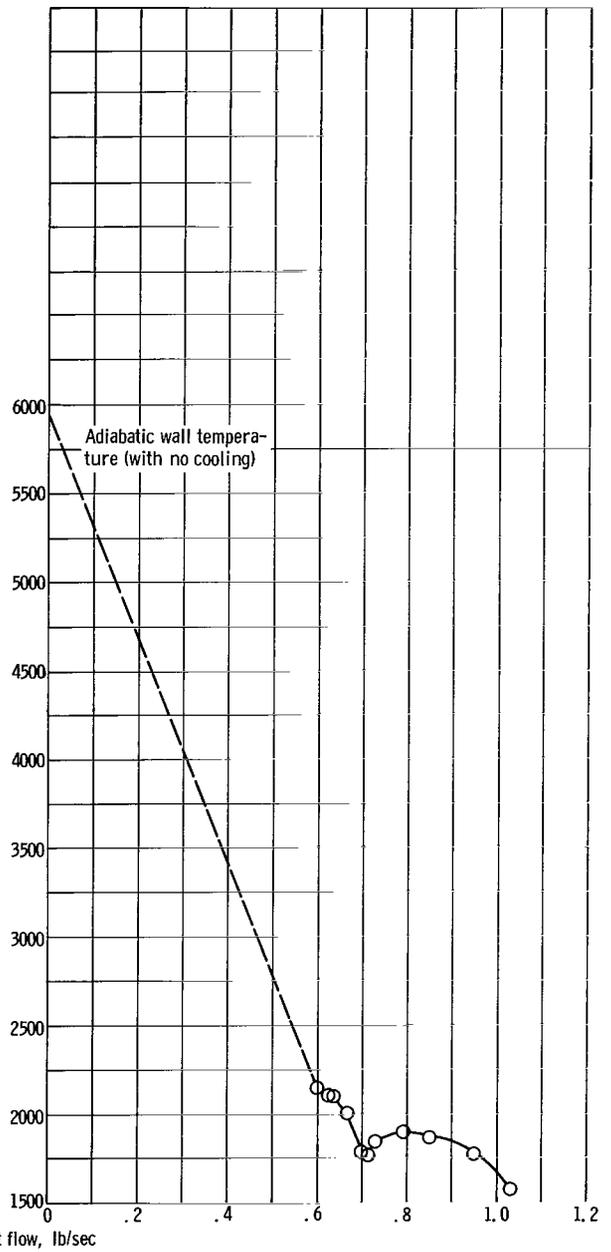
Data from the 11 firings with the 0.045-inch coolant injection slot were plotted as equilibrium wall temperatures against coolant flow for each of the 11 axial measuring stations, and these data are presented in figures 8(a) and (b). These curves exhibit the expected generally negative slope overall, but have a pronounced and unexpected depression at a coolant flow of approximately 0.70 to 0.71 pound per second. This depression, which amounts to about 200° to 250° R, represents quite a sizeable decrease in wall temperature below the level to be expected from the normal negative-slope curve, and nothing in the known gaseous-film cooling correlations would indicate this type of behavior. Should this depression be a predictable phenomenon, and it certainly is not at



(a) Measuring stations nearest coolant slot.



(b) Measuring stations furthest from coolant slot.



(c) Axial station 6.

Figure 8. - Wall temperature as function of coolant flow. Slot height, 0.045 inch; temperatures are circumferential averages of 3 thermocouples except as noted.

present, it would offer the designer of a gaseous-film cooling application the possibility of optimizing his design, inasmuch as the coolant weight flow at the depression is some 25 percent below the higher flow at which the same wall temperature will result. However, to place the value of this phenomenon in its proper perspective, a sample of the data on figure 8(a) (that at station 6) is shown in figure 8(c) with the curve extrapolated to the adiabatic wall temperature at zero coolant flow. The depression, while appreciable and possibly useful, is relatively small compared to the more general results of gaseous-film cooling.

The film coolant injection slot height was decreased from 0.045 to 0.040 inch after the preceding group of firings for two reasons: (1) to determine if this variable would satisfy the correlating equation, and (2) to determine if any functional relation could be observed that might help account for the depression in the curves of wall temperature as a function of coolant flow. It was thought that the temperature depression could possibly be a function of the ratio of coolant to hot-gas velocity at the injection point, and with the change in coolant slot height the depression at a given velocity would be moved to a different, presumably lower, coolant flow that would give an indication of the nature of the phenomenon.

Equilibrium wall temperature data from 8 of the 11 firings with the 0.040-inch slot height are given in figure 9. Slight depressions in the curves exist at coolant flows of approximately 0.69 and 0.613 pound per second. However, these depressions are not sufficiently deep to be considered

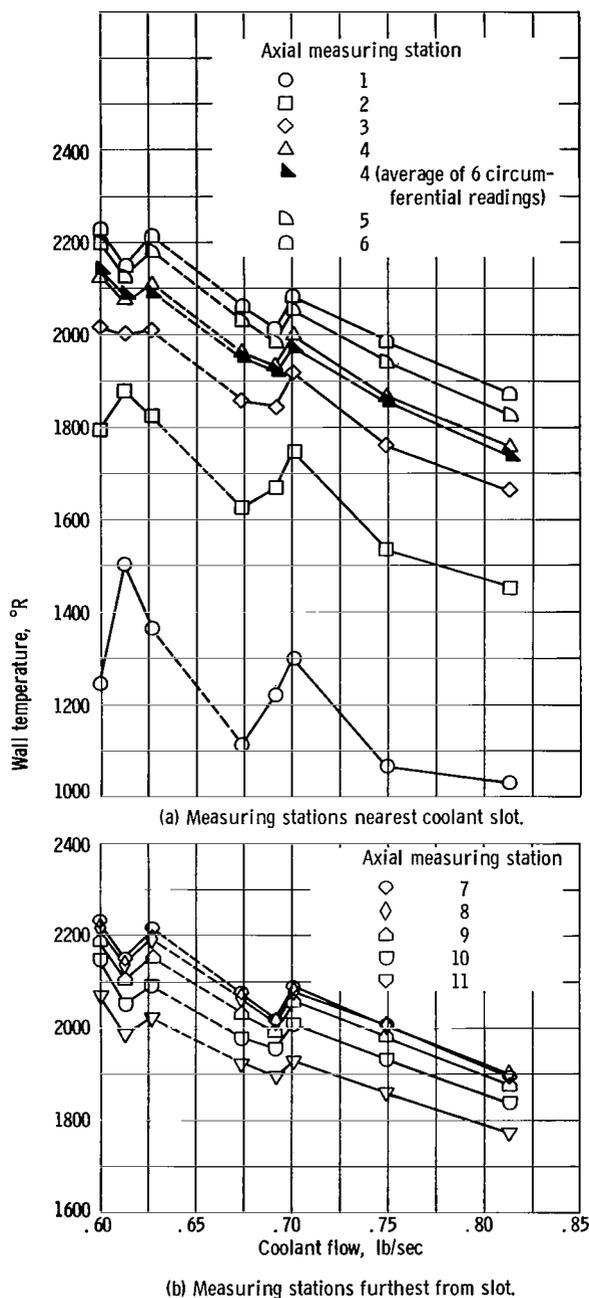


Figure 9. - Wall temperature as function of coolant flow. Slot height, 0.040 inch; temperatures are circumferential averages of 3 thermocouples except as noted.

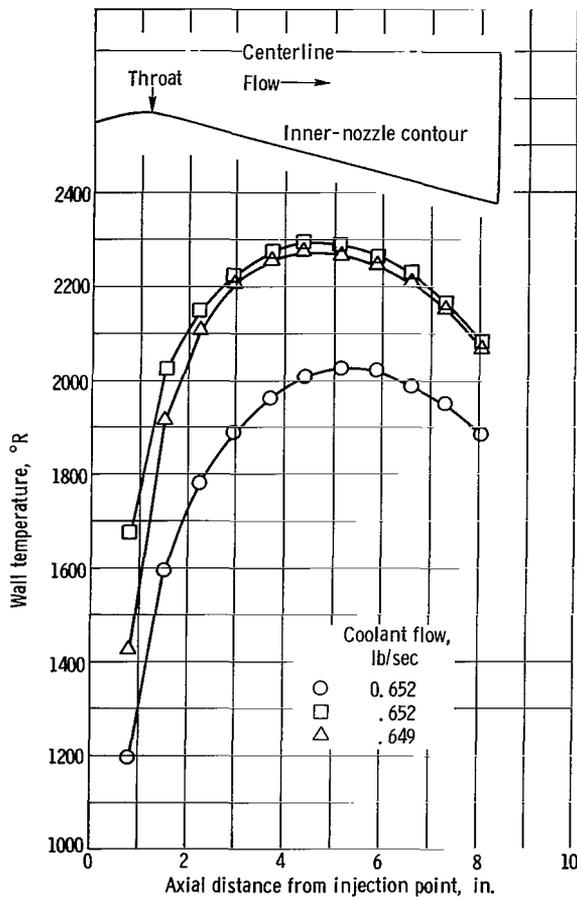


Figure 10. - Wall temperature distribution after three separate firings. Slot height, 0.040 inch; coolant flow, approximately 0.65 pound per second.

definitive. The remaining 3 firings with the 0.040-inch coolant slot height were with a coolant flow of from 0.649 to 0.652 pound per second. These three firings, at a virtually constant coolant flow, produced equilibrium wall temperatures that, at a given axial station, varied by as much as 470°R , as shown in figure 10. These data, at a coolant flow in the center of the dashed area in the curves of figure 9, fall both well above and well below the general trend of the data of figure 9.

The conclusion to be drawn from the various data with the 0.040-inch coolant slot height is that below a coolant flow of about 0.70 pound per second only a general trend of equilibrium wall temperatures can be observed, with considerable possibility of appreciable scatter present. This conclusion does not help to define any possible depression in this data corresponding to that noted with the 0.045-inch coolant injection slot, which in turn precludes the possibility of determining any functional relation concerning the noted depression. With the limited data available, it must be concluded that

equilibrium wall temperatures can exhibit a somewhat anomalous behavior with respect to coolant flow variation at different coolant injection slot heights, and that the reasons for such behavior are not known. These reasons would definitely be of interest in a detailed study of gaseous-film cooling, and would probably throw considerable light on the behavior of the gaseous-film cooling process in the very complex interacting flow fields of the film-cooled rocket nozzle.

Data Correlation

The equilibrium wall temperature data obtained with the 0.045-inch coolant slot height are presented in figure 11, and the data obtained with the 0.040-inch coolant slot height are presented in figures 12 to 14, all in the form of a modification of the Hatch-

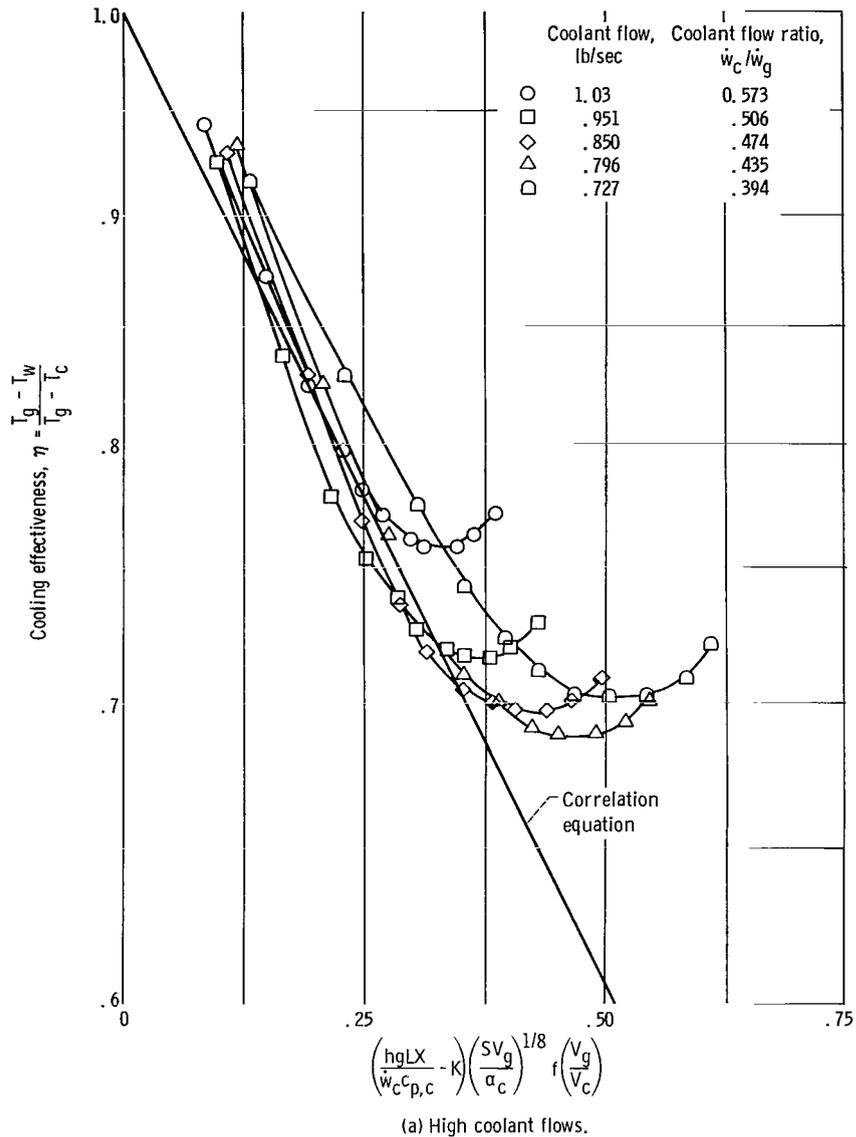
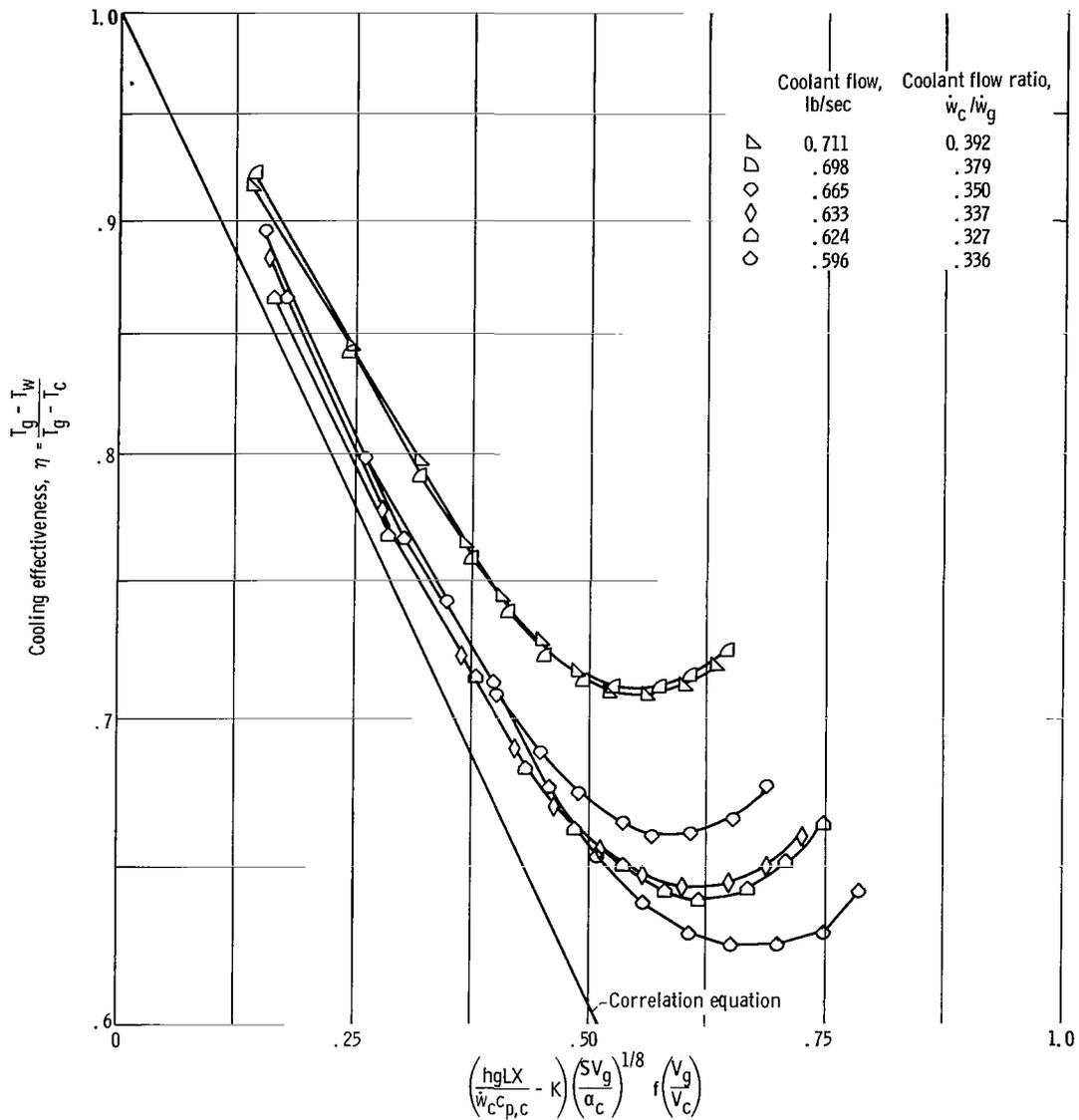


Figure 11. - Effectiveness as function of correlating parameter over range of coolant flows. Slot height, 0.045 inch; constant K, 0.

Papell equation of reference 3. The modification to the equation involves the terms T_g and hgL , both of which are discussed in appendix B, and K , which is also mentioned but not discussed in appendix B. A change in K will shift a data curve on the Hatch-Papell coordinates to higher or lower values of the abscissa without altering its shape. Such a change was found necessary in reference 5 to yield proper apparent correlation of the data obtained in the cylindrical portion of the combustion chamber, with a progressively lesser change required for data obtained down the convergent portion of the nozzle. The change in K was justified on the basis of a large increment of wall temperature rise



(b) Low coolant flows.

Figure 11. - Concluded.

apparently caused by hot-gas radiation, although other unknown factors undoubtedly were also present.

It was necessary to change the value of K from 0.04, as used in reference 3, to 0 to properly correlate the bulk of the present data. The reasons for the necessity of this change are not known, but could presumably include pressure gradient effects (possibly combined with coolant film thickness variation along the nozzle), hot-gas radiation, stream-mixing and interactions at the injection point caused by velocity and static-pressure differences and the presence of the relatively thick slot lip, etc. In all probability, the true total effect is an undefinable combination of many conditions, though a

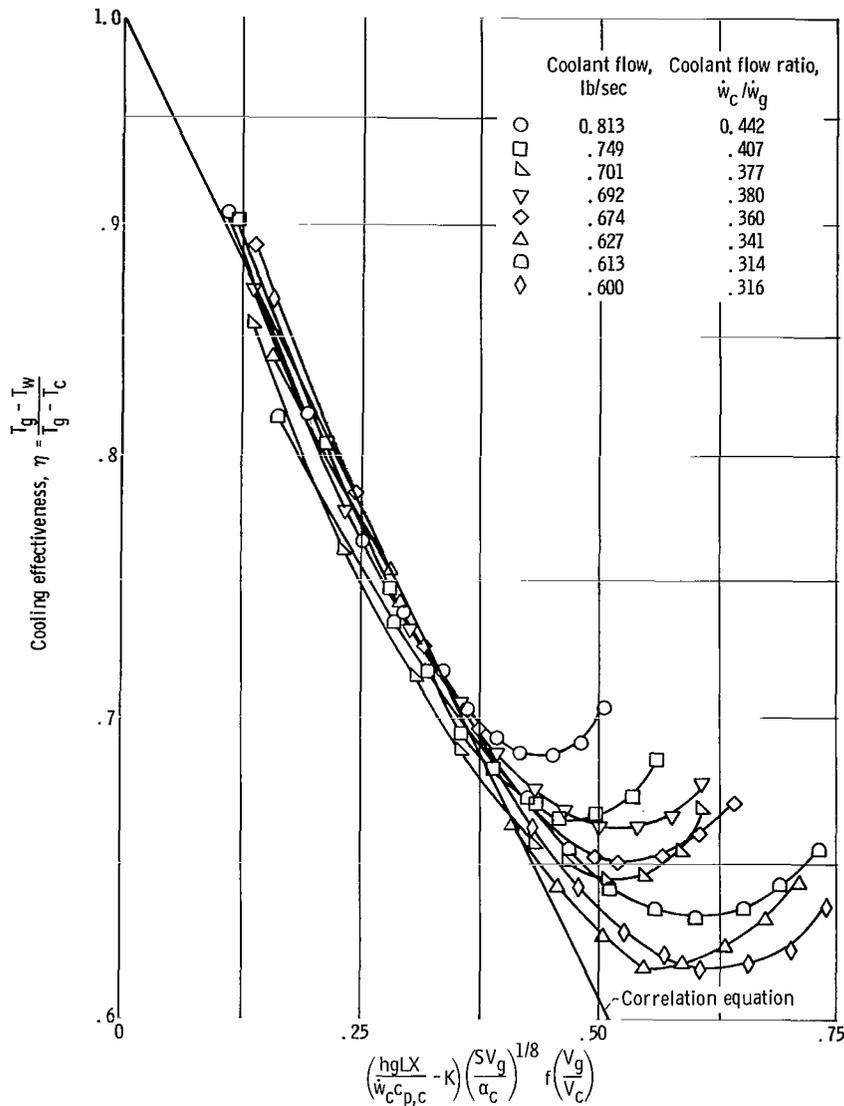


Figure 12. - Effectiveness as function of correlating parameter over range of coolant flows. Slot height, 0.040 inch; constant K, 0.

greater accumulation of data should permit determination of gross effects of some of the more important parameters. The effect of a change in K in correlating the present data could also be obtained by a separate additive term in the correlating equation, the technique used in reference 4 in connection with the effect of nontangential film-coolant injection.

Over the usable axial range of wall temperature data, neglecting that from the last four measuring stations, the modified correlating equation satisfies the data quite well, as evidenced by figures 11 to 14. The only exceptions to this conclusion were the data in figure 11 taken at the coolant flows that indicated depressed wall temperatures with

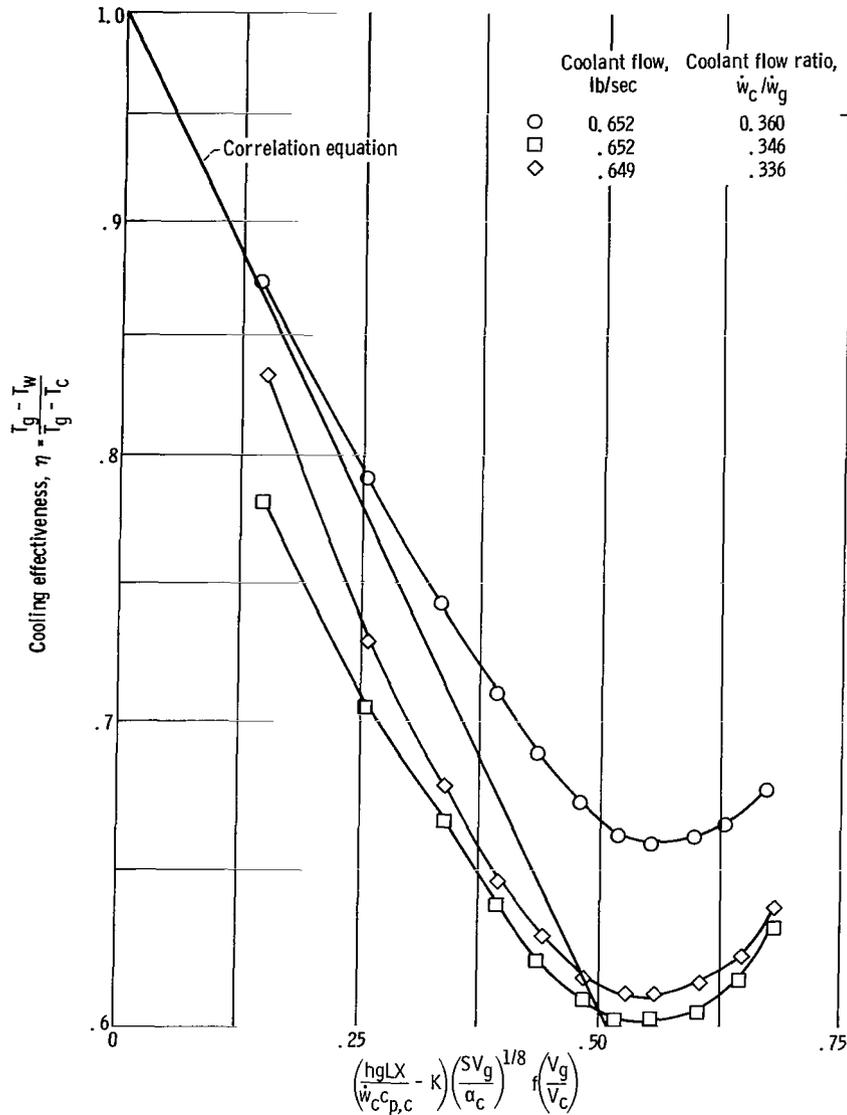


Figure 13. - Effectiveness as function of correlating parameter after three separate firings. Slot height, 0.040 inch; constant K , 0; coolant flow, approximately 0.65 pound per second.

the 0.045-inch slot height, and the data in figure 13 taken with the 0.040-inch coolant slot height at a coolant flow of about 0.650 pound per second, which was in the coolant flow range where inconsistent and anomalous equilibrium wall temperatures were observed. The distance along the nozzle over which satisfactory correlation was obtained includes the entire region surrounding the throat, the area of greatest interest in auxiliary cooling schemes.

The appearance in figures 11 to 14 of the data at the downstream end of the nozzle (from the last 4 axial measuring stations) suggests that the Hatch-Papell correlation is not particularly applicable at this distance from the coolant injection slot. The same

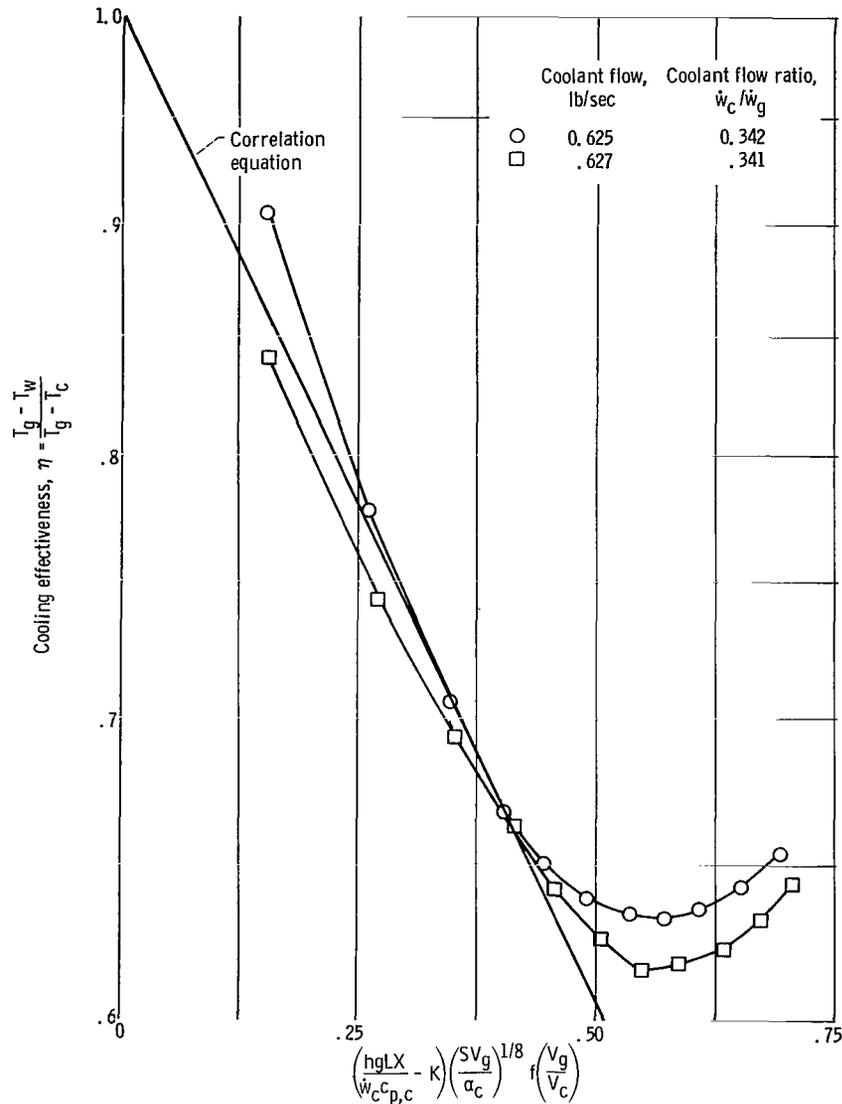


Figure 14. - Effectiveness as function of correlating parameter after two separate firings. Slot height, 0.040 inch; constant K, 0; coolant flow, approximately 0.625 pound per second.

general observation can be made from the data of references 3 to 5. A portion of the poor appearance of correlation with the present data can be explained by the comparatively low heat-transfer coefficient and low hot-gas temperature at the downstream end of the nozzle combining to necessitate an extra long time for the wall temperatures to reach equilibrium. However, it appears that the major cause for the poor correlation lies with the inability of the simple heat-flow model on which the equation is based to adequately describe the complex heat- and fluid-flow situation at comparatively great distances downstream of the coolant injection slot. Indeed, it has been suggested that this correlation should be replaced by a boundary-layer form of correlation at about 100 slot

heights downstream of the coolant injection slot; these 100 slot heights would eliminate the last four or five measuring stations from consideration by the present correlation scheme. This suggestion seems to agree rather well with the appearance of the present data. The use of the present equation in a design would at least result in conservative wall temperature predictions far downstream.

Considerations on Design of Film-Coolant Injector

Although this report is intended primarily to present data obtained with a gaseous-film-cooled rocket motor and subsequent correlation of these data, it would seem appropriate to record some observations of a more mechanical nature which might relate to the practical application of gaseous-film cooling. These remarks will apply only to the case of tangential (or near-tangential) coolant injection through a wall slot, a situation which requires the use of a thin lip to direct the flow along the wall; the lip is thus exposed on one side to the hot gases.

Reference 5 stated that unsupported lips for film-coolant injectors were unsatisfactory because thermal expansion caused the lip to move outward; this outward expansion tends to decrease, and possibly eliminate, the narrow annular slot. Any circumferential distortion of heat flux would cause an uneven expansion of the lip, which could cause local closing of the slot at just the circumferential location where cooling was most needed.

In view of the disastrous results expected with slot-lip expansion, it seemed obvious that some form of support was needed for this item. The method chosen both in reference 5 and the present investigation was to support the lip with spacers whose height was equal to the slot height, with a width of about 0.025 inch, a length of about 0.12 inch, and a spacing of about 0.32 inch circumferentially, as shown by the sketch in figure 3. For the first firing in the present investigation, the slot lip overhung the lip spacers by approximately 0.10 inch. Post-firing examination of this lip showed clearly that the combination of buckling expansion between the spacers and full-circumferential expansion of the overhung lip caused the edge of the lip to contact the outer wall between the spacers (fig. 15). The blackened areas of the lip edge (fig. 15) between the indentations caused by the spacers indicate the areas where wall contact occurred. All the firings reported herein were made with a modified lip which overhung the lip spacers only 0.020 inch. Although these lips could reasonably be expected to expand and buckle somewhat between supports, no trouble was experienced with them.

Figure 15 also indicates the lip expansion in another way. Post-firing indentations on the lip caused by the spacers are clearly evident in the photograph. These indentations are approximately a quarter-thousandth inch deep and are caused by radial

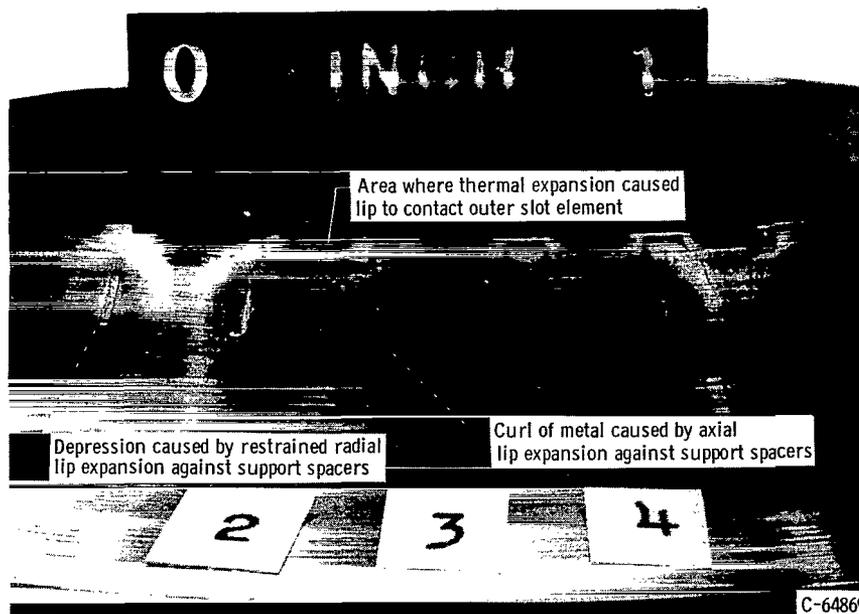


Figure 15. - Indentations and discolorations on slot lip after firing.

expansion of the lip. A small curl of metal at the upstream end of the indentation (bottom of photograph) indicates that the lip also expanded along the axis of the motor in the direction of coolant flow (upward in photograph). This distortion of the metal indicates the existence of quite high force between the slot lip and the spacers. The considerable force involved in the lip expansion also caused the compressive hoop stress in the lip to exceed the metal yield point with the result that when the lip was quenched by the cold purge gas at the termination of firing, it shrank by about 3 percent from its original diameter.

The film-coolant injection slot lip has been shown to be a potentially critical component in a design, and would require considerable thought and development for an actual application. For example, the lip would have to be restrained from inward as well as outward movement on a restartable engine to prevent too large a slot height at the start of a second firing due to lip shrinkage after the first firing. This problem could be made somewhat less severe in a tube-walled engine by using a corrugated lip, restrained between tubes, with the corrugations following the tube wall contours. Here, at least, any circumferential expansion of the lip would open rather than close the coolant slot, and would not cause compressive stresses to exceed yield values. This corrugated lip would have the additional advantage of placing the lip supports in the valleys of the tube wall where heat-transfer coefficients and wall temperatures are lowest and the need for film coolant is lowest. As shown in figure 16, the lip supports do adversely affect circumferential coolant distribution for a considerable distance downstream of the injection

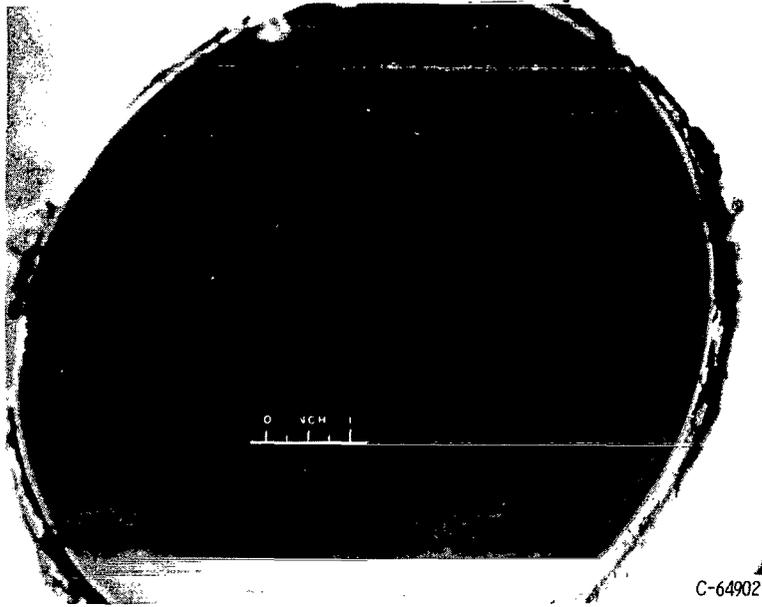


Figure 16. - Discolorations inside nozzle (looking upstream) downstream of slot-lip supports after firing.

location. In addition to this alteration in flight-type hardware, the slot lip should be as thin as reasonably possible to lessen the initial turbulent mixing of coolant and hot gas which almost certainly occurs downstream of the thick lip of the present investigation.

The comments on the problems associated with the lip of a tangential coolant injection slot might suggest that in a critical application some other form of injection scheme would be required. For example, an angled slot, a series of angled holes, or a porous wall section might prove to be a mechanically feasible injection method where the tangential slot lip could not be adequately cooled. In this case, the designer would have to accept the poorer downstream cooling performance of the nontangential coolant injector discussed in reference 4.

CONCLUDING REMARKS

Mention has been made of the very high values of the ratio of film-coolant mass flow to mainstream mass flow quoted herein. These values, 0.316 to 0.573, would be unacceptable in a flight-type rocket motor due to the heavy load of coolant that would have to be carried. The nitrogen coolant used in this experiment would be a poor choice for a flight application due to its high molecular weight and consequent low specific heat. Hydrogen would almost certainly be used as the film coolant in the flight application, although helium would be usable in a rocket motor that for some reason might require an inert coolant gas. Hydrogen, with a specific heat 14 times that of nitrogen, would, to a

first approximation at least, reduce the coolant-to-hot-gas mass flow ratios by a factor of 14, bringing the values for this experiment down to 0.023 to 0.041. In addition, hydrogen has a much higher sonic velocity than nitrogen, which had a sonic velocity of about one-half the mainstream velocity at the injection point in the present experiment. This relatively high sonic velocity would allow the film coolant injector to be designed so as to match the coolant velocity with the hot-gas velocity, which would in turn allow more effective use of the coolant because of the lowered chance for turbulent mass interchange between streams. Lowering the chance for turbulent mass interchange would have the effect of requiring an even lower coolant mass flow ratio with hydrogen than the figures quoted.

The preceding arguments would seem to indicate that, for the present rocket motor, a coolant flow of something less than 2 percent of the propellant flow would be required. As the cooling problem becomes more severe (e. g. , at a higher chamber pressure), the coolant flow percentage could become slightly lower because the heat-transfer coefficient, and thus the required coolant flow, varies as the propellant flow to the 0.8 power. In addition, most of the foreseeable rocket motor applications of gaseous-film cooling would use this method in combination with convective wall cooling, which would probably lower the film-coolant flow ratio to the 1-percent range.

The degradation to be expected in engine performance would be very small with a film-coolant flow rate of around 1 percent. With hydrogen as the film coolant and combustion products of a higher molecular weight, as would be the case in all chemical rockets, the degradation in performance could conceivably become an enhancement because of the high specific impulse of hydrogen heated to expected wall temperature levels.

SUMMARY OF RESULTS

An experimental investigation of gaseous-film cooling of the nozzle of a small JP-4 - gaseous-oxygen rocket motor was conducted using tangentially injected nitrogen as the coolant. The following results were obtained:

1. Gaseous-film cooling of a rocket nozzle can be accomplished with coolant injection into the subsonic accelerating flow field with cooling lasting along the full length of the throat and divergent portions of the nozzle.
2. The adiabatic wall temperature distribution downstream of the film-coolant injection slot was correlated to a significant distance beyond the nozzle throat by the Hatch-Papell relation, with hgL (heat-transfer coefficient times engine circumference) used as an integrated average from the coolant injection station to the separate data stations. In addition, both a change in the constant K from 0.04 to 0 and the use of local hot-gas static temperature as the driving temperature T_g were required to achieve apparent correlation of the present data.

3. Over a portion of the coolant flow range with the 0.045-inch slot height, there appears to be anomalous behavior in the downstream adiabatic wall temperature pattern, which suggests a possibility of coolant flow optimization which cannot be determined from the Hatch-Papell relation as it presently exists.

4. The lip of the tangential coolant injection slot is a critical component due to thermal expansion with resulting distortion and heavy compressive stresses. This item would require very careful design in a flight application to avoid the effects of thermal expansion and to minimize the disturbing effects on coolant flow of both the lip thickness and the lip supports. In a critical application, the use of nontangential coolant injection might therefore be required to eliminate the lip and its problem.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 14, 1966,
122-29-07-03-22.

APPENDIX A

SYMBOLS

$c_{p,c}$	coolant specific heat	V_c	coolant velocity
f	function	V_g	hot-gas velocity
hg	hot-gas heat-transfer coefficient	\dot{w}_c	coolant flow rate
$(hgL)_0^X$	integrated average of hgL from coolant injection station to station at distance X	\dot{w}_g	propellant flow rate
K	constant, 0.04 with only convective heat transfer	X	surface distance downstream of coolant injection slot
L	cooled width (local circumference at any given axial station in nozzle)	X_n	surface distance at axial station n , see fig. 3
n	axial station, see fig. 3	Z_n	axial distance at axial station n , see fig. 3
R_n	radius at axial station n , see fig. 3	α_c	coolant thermal diffusivity
S	coolant slot height	β	coolant injection angle relative to wall
T_c	coolant temperature	β_{eff}	effective coolant injection angle, $\tan^{-1} \frac{\sin \beta}{\cos \beta + \frac{\rho_g V_g}{\rho_c V_c}}$
T_g	hot-gas temperature (assumed to equal local static temperature)	η	cooling effectiveness
T_w	wall temperature	ρ_c	coolant mass density
		ρ_g	hot-gas mass density

APPENDIX B

SAMPLES OF VARIOUS ATTEMPTED DATA CORRELATION SCHEMES

The data from the present experimental investigation were calculated for use with the Hatch-Papell equation in different ways to determine the method which resulted in the best apparent correlation. The effects of changing some of the parameters in the calculations will be illustrated with the data obtained at a coolant flow of 0.692 pound per second and a coolant slot height of 0.040 inch.

The first calculation uses the flat-plate method of reference 3, with T_g equal to the hot-gas total temperature and h_g and L considered constant values existing at the coolant injection point. The result is plotted in figure 17 as curve A. The poor agreement is easily noted. The last 2 points at the downstream end of the nozzle are off the figure to the right. With the same constant values of T_g and L but with local values of h_g used in the calculations, curve B results, again in poor agreement with the Hatch-Papell equation. Curve C, calculated with the same constant values of T_g and L but with h_g used as an average between the local value and the injection station value, as might be considered reasonable from the results of reference 5, appears to at least approach the proper slope over a portion of its length. Correlation, however, is still far from satisfactory.

These methods, and many other possible methods of calculation, are not satisfactory, and they in fact constitute mere juggling of terms in the hope that apparent correlation will result. In reference 3, the terms h_g and L were specified as constants because the uniformly heated, constant-width, flat-plate model was satisfied by such a specification. These two terms in the correlation form parts of a representation of the total amount of heat which the hot-gas has transferred to the coolant gas as the coolant gas has moved from the injection point to a given downstream data station. It is this amount of heat given to the coolant gas in its travel to the station under consideration which determines the temperature of the gas at that station, and thus the wall temperature at that station. A true representation of $h_g L$ for a given station would then be an integrated average of that term over the distance from the coolant injector to the given station. For the flat plate of reference 3, $h_g L$ would reduce to the constant values used in that reference. For the nozzle of the present investigation, $h_g L$ would be far from constant.

The experimentally determined value of the heat-transfer coefficient h_g at each axial station is presented in table III. These values were obtained from a faired curve of data presented in part in reference 5 along with a discussion of the method by which it was obtained. Values of the product of h_g from this table times the local value of L calculated from the nozzle dimensions of figure 3 were plotted against axial distance,

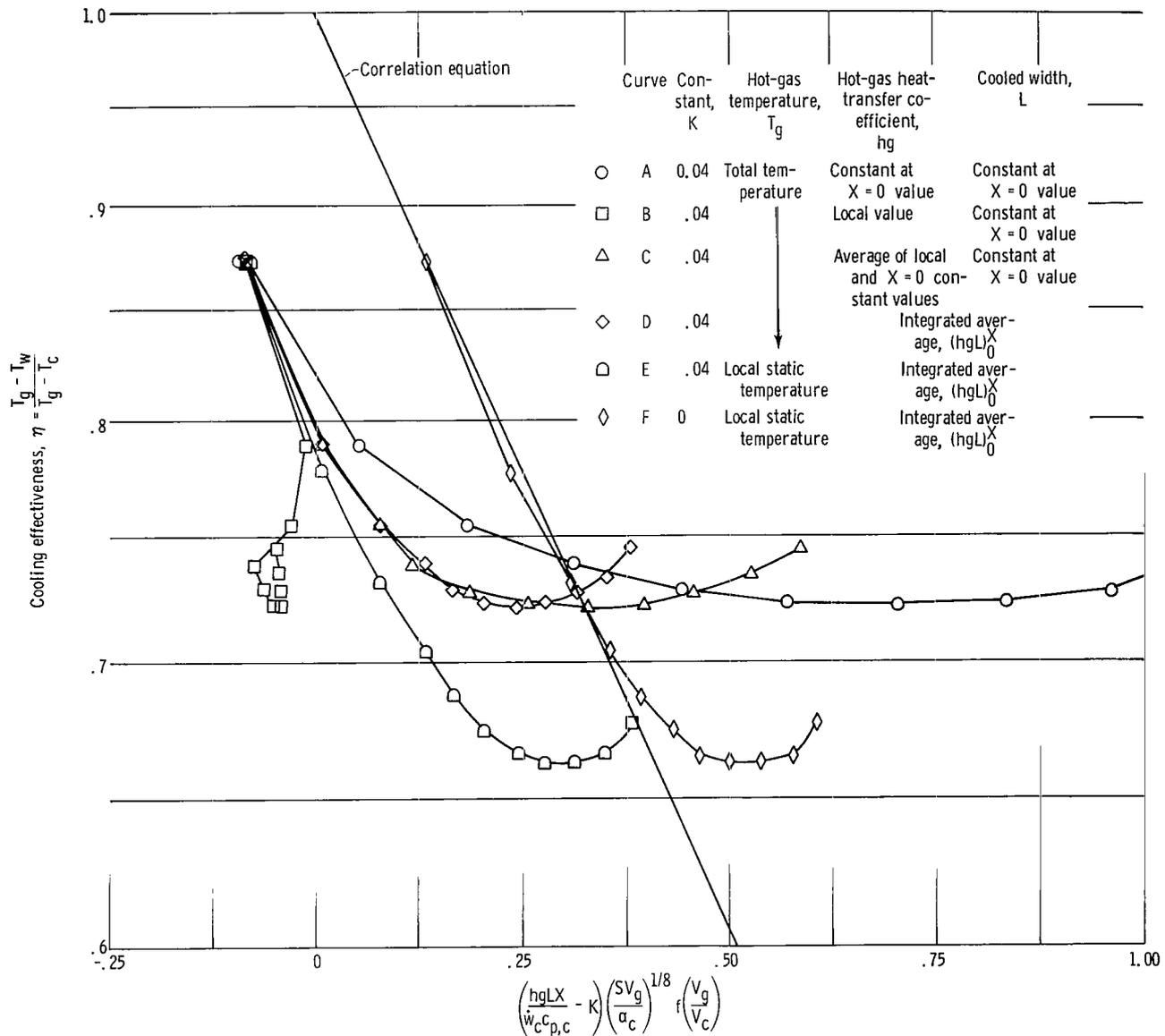


Figure 17. - Several ways to present gaseous-film cooling data. Slot height, 0.040 inch; coolant flow, 0.692 pound per second.

TABLE III. - EXPERIMENTAL HEAT-TRANSFER COEFFICIENTS

Axial station	Hot-gas heat-transfer coefficient, hg, Btu/(sq ft)(sec)(°R)	$(hgL)_0^X$, Btu/(ft)(sec)(°R)
1	0.0795	0.0603
2	.0626	.0551
3	.0395	.0491
4	.0227	.0431
5	.0194	.0384
6	.0174	.0352
7	.0155	.0329
8	.0140	.0308
9	.0124	.0296
10	.0112	.0284
11	.0100	.0273

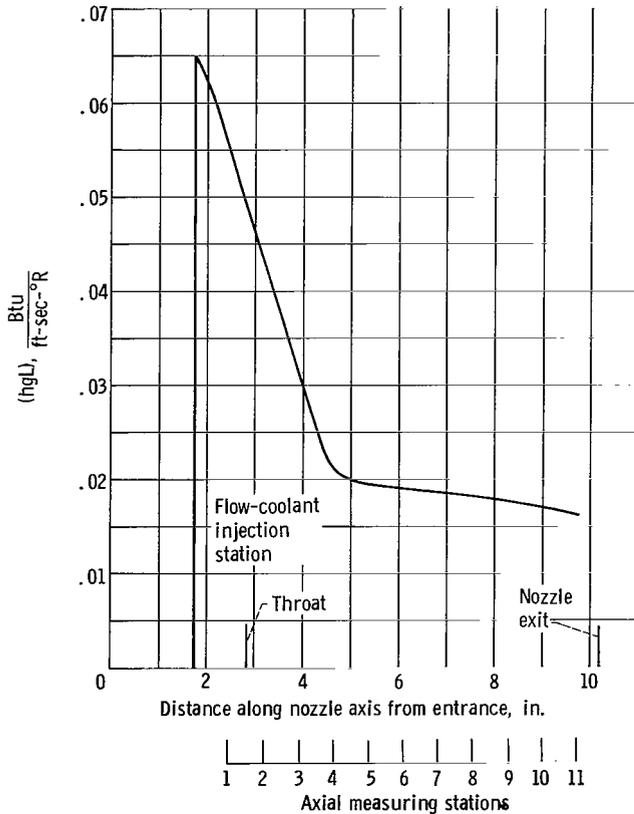


Figure 18. - Curve for determination of local values of $(hgL)_0^X$ through the nozzle.

and the resulting curve is presented in figure 18. This curve was then integrated from the coolant injection point to each measuring station to obtain local values of $(hgL)_0^X$ at each station, which are also presented in table III. Curve D on figure 17 shows the sample data calculated by using these values of $(hgL)_0^X$ and the same total value of T_g . Unfortunately, with the exception of the data at the downstream end of the nozzle the appearance of this curve is not significantly better than curve C, due to some compensations between the values of L and hg . However, curve E, which has local values of hot-gas static temperature substituted for the total values of T_g in the calculation of the effectiveness, and with the integrated average values of $(hgL)_0^X$, appears to offer a far better approach to the slope of the correlating equation over the usable range of data. There is no good reason for

the use of static values of hot-gas temperature rather than the total value (in fact, this violates the heat-flow model from which the Hatch-Papell equation was derived) except for the considerably better appearance of correlation with static values. It would seem more likely that the true, unknown effect which corrects the data curve should be introduced into the right side of the correlating equation rather than the left.

Curve F presents the same data as curve E, except that the value of the constant K has been changed from 0.04 to 0. This change was made solely to move the data curves to higher values of the correlating parameter so that they will roughly coincide with the equation of the correlation. A goodly portion of the data now is represented by the equation, and the equation would at least yield conservative temperatures for the downstream end of the nozzle, where the appearance of correlation is poor.

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