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EFFECTS OF REGENERATIVE AND RADIATION COOLING ON PERFORMANCE OF ELECTROTHERMAL THRUSTORS

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SUMMARY

The effects of regenerative and radiation cooling on thrustor performance, as judged by the specific impulse, are presented for a frozen flow with a constant input power and propellant flow rate.

In general, the performance gains to be achieved by regenerative cooling are strongly dependent on such operating parameters as gas enthalpy, wall temperature, and amount of regenerative cooling. For example, when the frozen-flow efficiency decreases with increasing gas enthalpy, increased regenerative cooling results in a small gain or a loss in performance, depending on the wall temperature. When the frozen-flow efficiency increases with increased enthalpy, however, significant performance gains due to regenerative cooling can be anticipated, regardless of the assumed wall temperature.

INTRODUCTION

The basic cooling schemes for dissipating the heat load of an electrothermal thrustor are radiation cooling, in which the heat is dissipated by radiation from the outer surface of the thrustor body, regenerative cooling, in which the propellant absorbs the heat in passing through passages in the thrustor body, and, finally, partial regenerative cooling, a combination of radiation and regenerative cooling. A general discussion of these schemes and their limitations is presented in reference 1. Regenerative cooling, as contrasted with radiation cooling, offers the advantage of allowing recovery of some or all of the thrustor heat loss and therefore substantial increases in thrustor performance. Also, regenerative cooling may allow a reduction in the wall temperature, which can alleviate to some extent the materials problem associated with thrustors. With reduced wall temperature the thrustor heat loss is, of course, increased, but with regenerative cooling it is recoverable. Thrustor performance, therefore, might again be expected to exceed that for the comparable radiation-cooled thrustor. For equilibrium flow this is indeed the case. For frozen flow, however, because of the effect of regenerative cooling on the frozen loss, the situation may be quite different. The following analysis and examples serve to illustrate this point.

SYMBOLS

A_N	inside surface area of thrustor nozzle, sq cm
C_Q	overall heat-flux coefficient, kw/°K
g	gravitational constant
H_{ex}	nozzle-exit enthalpy, cal/g
H_F	frozen-flow enthalpy, cal/g
H_{gas}	gas enthalpy, cal/g
H_J	jet enthalpy, cal/g
H_W	enthalpy associated with wall temperature T_W and local pressure, cal/g
I	specific impulse, sec
J	Joule's constant
P_E	electrode power loss (in form of heat), kw
P_{ex}	thermal power loss, available energy not converted to kinetic energy, kw
P_F	frozen-flow power loss, power loss due to dissociation and ionization of propellant, kw
P_{gas}	propellant power after energy addition, kw
P_I	power input to thrustor, kw
P_J	jet or thrust power, kw
P_Q	nozzle-heat power loss, kw
P_R	power absorbed regeneratively, $0 \leq P_R \leq (P_E + P_Q)$, kw
p_o	plenum-chamber pressure, atm
T_{gas}	gas temperature, °K
T_W	wall temperature, °K
$\dot{w}$	propellant flow rate, g/sec
ϵ	regenerative fraction
η_A	arc heater efficiency

η_F frozen-flow efficiency

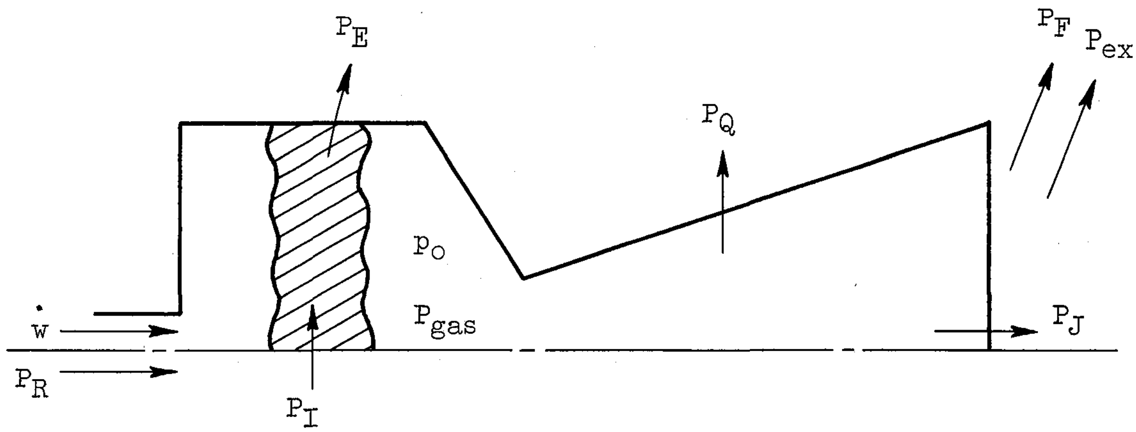
σ Boltzmann's constant

Subscript:

max maximum

ANALYSIS

A schematic of an arc-jet thrustor, including the pertinent power terms, is shown in the following sketch:



A simple power balance yields

$$P_J = P_{gas} - P_Q - P_F - P_{ex} \tag{1}$$

and

$$P_{gas} = P_I - P_E + P_R \tag{2}$$

In terms of the jet and gas enthalpies, equations (1) and (2) become

$$H_J = H_{gas} - \frac{P_Q}{\dot{w}} - H_F - H_{ex} \tag{3}$$

and

$$H_{gas} = \frac{P_I}{\dot{w}} - \frac{P_E}{\dot{w}} + \frac{P_R}{\dot{w}} \tag{4}$$

When the nozzle-exit pressure is assumed equal to the ambient pressure, the specific impulse is given by

$$I = \frac{1}{g} \sqrt{2gJH_J} \tag{5}$$

A qualitative discussion of the effect on thrustor performance of increasing the fraction of the heat loss absorbed regeneratively (and thereby decreasing the fraction of the heat lost by radiation) is now possible. It is first assumed that the input power P_I obtained from an electric power source and the propellant flow rate $\dot{w}$ are constant. The problem then is to maximize the effective jet power P_J and thereby obtain the maximum overall thrustor efficiency; however, P_J is equal to $\dot{w}H_J$, which in turn is proportional to $\dot{w}I^2$. Consequently, the criterion for thrustor performance improvement is taken to be an improvement in the specific impulse or H_J since this corresponds to increased thrust, jet power, and efficiency for the given power input and propellant flow rate.

Equation (2) shows that an increase in P_R results in an increase in the gas enthalpy H_{gas}. From equation (3), for equilibrium flow ($H_F = 0$), it can be seen that this increase in H_{gas}, which preliminary calculations have shown to be considerably greater than any increase in $P_Q/\dot{w}$, will result in sizable gains in the jet enthalpy H_J. For equilibrium flow, therefore, an appreciable increase in thrustor performance can be expected with increased regenerative cooling. For frozen flow, however, the increase in gas enthalpy may result in a significant increase in the frozen-flow power loss P_F as well as in the nozzle-heat power loss P_Q, and, therefore, the performance gains may not be as great as for equilibrium flow. The case for regenerative cooling when the flow is frozen is therefore not clearly established.

A more detailed analysis is now given to illustrate the previous statement. The nozzle heat loss (the convective heat transfer to the nozzle walls) for frozen flow may be expressed approximately as

$$P_Q = C_Q(T_{gas} - T_W) \tag{6}$$

where C_Q is an overall heat-flux coefficient, which depends on operating conditions. The electrode power loss may be expressed in terms of an arc heater efficiency η_A as

$$P_E = (1 - \eta_A)P_I \tag{7}$$

The fraction of the power loss $P_E + P_Q$ that is regeneratively absorbed by the propellant is denoted by

$$\epsilon = \frac{P_R}{P_E + P_Q} \tag{8}$$

The fraction of $P_E + P_Q$ that is not absorbed regeneratively must be radiated away and is, therefore, equal to $1 - \epsilon$. Thus, completely radiative cooling corresponds to $\epsilon = 0$, and completely regenerative cooling corresponds to $\epsilon = 1$. The amount of regenerative cooling P_R possible is limited, however, by both the propellant and the thrustor geometry. The propellant limitation is given, as in reference 1, by

$$P_{R,max} = \dot{w}H_W \tag{9}$$

where H_W is the enthalpy associated with the wall temperature T_W and the local pressure. The limitation imposed by the thrustor geometry results from the radiation loss associated with the inside surface of the nozzle. Since this surface area is never zero, power is always being radiated away. Consequently, the geometry limitation on P_R is given by

$$P_{R,max} = P_E + P_Q - \epsilon\sigma T_W^4 A_N \tag{10}$$

This latter limit is not applied herein since a nozzle geometry must be specified. When the results of the analysis are used, however, this limit can be applied for the nozzle geometry of interest.

By substitution from equations (6) to (8), equations (3) and (4) become

$$H_J = H_{gas} - \left(\frac{C_Q}{\dot{w}}\right)(T_{gas} - T_W) - H_F - H_{ex}$$

$$= \eta_F H_{gas} - \left(\frac{C_Q}{\dot{w}}\right)(T_{gas} - T_W) - H_{ex} \tag{11}$$

where η_F is the frozen-flow efficiency and

$$H_{gas} = \eta_A \frac{P_I}{\dot{w}} + \epsilon\left[(1 - \eta_A) \frac{P_I}{\dot{w}} + \left(\frac{C_Q}{\dot{w}}\right)(T_{gas} - T_W)\right] \tag{12}$$

Since H_{gas} is related to T_{gas}, equation (12) must be evaluated by iteration. The power absorbed regeneratively is given by

$$P_R = \epsilon\left[(1 - \eta_A)\ P_I + C_Q\ (T_{gas} - T_W)\right] \tag{13}$$

and is limited according to equations (9) and (10).

EXAMPLES

The effect on thrustor performance of increasing the amount of heat absorbed regeneratively is best illustrated by an example. The most straightforward approach is to require a constant plenum-chamber pressure as well as a constant input power and propellant flow rate.[1] Hydrogen is chosen as the pro-

[1]The increase in plenum-chamber pressure due to increased regenerative cooling was determined to be at most 2 pounds per square inch for a constant nozzle geometry and the examples considered.

pellant. For these conditions the overall heat flux coefficient C_Q is approximately independent of ϵ, T_{gas}, and T_W.[2] The arc heater efficiency η_A may be expected to decrease only slightly with an increase in H_{gas} and also with an increase in ϵ. It is, therefore, correct to assume η_A to be nearly independent of ϵ. The expansion ratio is taken to be sufficiently large so that the thermal energy at the nozzle exit H_{ex} is negligible. The flow is assumed to be frozen at the composition corresponding to plenum-chamber conditions. The power input is 30 kilowatts, and the plenum pressure is 1 atmosphere. At these conditions, the specific-impulse levels selected for the radiation-cooled condition ($\epsilon = 0$) are 1000 and 1350 seconds. All the operating conditions assumed are given in table I. The variation of enthalpy with temperature for hydrogen is taken from reference 2. The frozen-flow efficiency, determined from the data of reference 3, is presented in figure 1. The engine wall-temperature conditions investigated for each case are (a) constant wall temperature independent of regenerative cooling and (b) reduced wall temperature and therefore increased heat loss, with increased regenerative cooling. The wall-temperature variation is arbitrarily assumed linear with ϵ and represents in each case a 1000° K decrease from $\epsilon = 0$ to $\epsilon = 1$.

The effect of regenerative cooling on thrustor performance, in terms of the specific-impulse ratio $I/I_{\epsilon=0}$, where $I_{\epsilon=0}$ is the specific impulse for radiation cooling, is presented in figure 2 for both sets of operating conditions. At a specific impulse $I_{\epsilon=0}$ of 1000 seconds (case 1) and a constant wall temperature, completely regenerative cooling results in only a 3-percent increase in specific impulse. If the wall temperature is allowed to decrease with increasing regeneration fraction, the performance actually decreases. The maximum regeneration fraction for this case based on equation (9) is $\epsilon = 0.78$, which corresponds to a 4-percent decrease in specific impulse over the comparable radiation-cooled thrustor. This is not too surprising when the variation of the frozen-flow efficiency with gas enthalpy is considered. Figure 1 shows that, at the point corresponding to case 1, an increase in gas enthalpy with increased regenerative cooling results in a significant reduction in frozen-flow efficiency. Therefore, most of the energy required to increase the gas enthalpy is being used to dissociate the hydrogen molecules, and thus the gain in jet enthalpy is quite small (eq. (3)). This effect together with the increase in heat loss (eq. (11)) limits the performance gains and, for a decreasing wall temperature, actually results in a decrease in performance.

It is also apparent from figure 1 that case 2 is quite different in terms of the frozen-flow efficiency. The frozen-flow efficiency increases with increasing regenerative cooling; that is, appreciable increases in H_{gas} result in small increases in H_F. Significant gains in performance can therefore be expected (case 2, fig. 2). At constant wall temperature, completely regenerative cooling results in a 26-percent increase in specific impulse. At a given regeneration fraction, the performance is only slightly affected by allowing a decrease in wall temperature. The maximum regeneration fraction for this case is limited to $\epsilon = 0.46$.

[2]The values of C_Q were obtained from the analysis of reference 2.

The effect of pressure on performance is also considered for the two extremes $\epsilon = 0$ and $\epsilon = 1$ and for a constant wall temperature. The conditions and corresponding results are as follows:

Specific impulse, $I_{\epsilon=0}$, sec	Plenum-chamber pressure, p_O, atm	Gas enthalpy, $(H_{gas})_{\epsilon=0}$, cal/g	Wall temperature, T_W, ^oK	Nozzle heat power loss, $(P_Q)_{\epsilon=0}$, kw	Specific-impulse ratio, $I_{\epsilon=1}/I_{\epsilon=0}$
1000	0.01	63.0×10^3	2500	2.0	----
	1	22.5	2500	2.0	1.03
	100	13.5	2500	2.0	1.07
1350	0.01	77.0×10^3	3000	1.5	1.21
	1	74.8	3000	1.5	1.26
	100	45.4	3000	1.5	1.06

Completely regenerative cooling at a specific impulse of 1000 seconds is not possible at a plenum pressure of 0.01 atmosphere since equation (9) is not satisfied. At a pressure of 100 atmospheres for this specific impulse the performance increase is somewhat greater than that at 1 atmosphere. For a specific impulse of 1350 seconds, the performance gains obtained with completely regenerative cooling are less at both high and low pressure than that obtained at 1 atmosphere. The increase in performance at a pressure of 100 atmospheres is considerably below that at the lower pressures. From figure 1 it is apparent that, at the gas enthalpies and pressures presented in the preceding table, large increases in performance occur when the frozen-flow efficiency increases, or remains nearly constant, with increased regenerative cooling (i.e., increased gas enthalpy). Small increases in performance occur when the frozen-flow efficiency decreases with increased ϵ.

CONCLUDING REMARKS

The change in electrothermal thrustor efficiency due to regenerative cooling has been considered for a frozen flow with fixed input power and propellant flow rate. It was found that the gains to be had are strongly dependent on such operating parameters as gas enthalpy level, wall temperature, and amount of regenerative cooling. For example, small or no performance gains can be expected when the frozen-flow efficiency decreases with increased gas enthalpy, that is, with increased regenerative cooling. Conversely, significant performance gains can be expected when the frozen-flow efficiency increases, or remains nearly constant, with increased regenerative cooling.

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National Aeronautics and Space Administration
Cleveland, Ohio, August 29, 1963

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2. Bartz, D. R.: A Simple Equation for Rapid Estimation of Rocket Nozzle Convective Heat Transfer Coefficients. Jet Prop., vol. 27, no. 1, Jan. 1957, pp. 49-51.

3. Rosenbaum, Burt M., and Levitt, Leo: Thermodynamic Properties of Hydrogen from Room Temperature to 100,000° K. NASA TN D-1107, 1962.

TABLE I. - OPERATING CONDITIONS ASSUMED FOR EXAMPLES

	Case 1	Case 2
Power input, P_I, kw	30	30
Plenum pressure, p_O, atm	1	1
Propellant flow rate, $\dot{w}$, g/sec	0.271	0.0815
Jet enthalpy, $(H_J)_{\epsilon=0}$, cal/g	11.50×10^3	20.94×10^3
Specific impulse, $(I)_{\epsilon=0}$, sec	1000	1350
Arc heater efficiency, η_A	0.85	0.85
Gas power, $(P_{gas})_{\epsilon=0}$, kw	25.5	25.5
Gas enthalpy, $(H_{gas})_{\epsilon=0}$, cal/g	22.5×10^3	74.8×10^3
Gas temperature, $(T_{gas})_{\epsilon=0}$, $^{\circ}$K	3300	5160
Average heat flux coefficient, C_Q, kw/$^{\circ}$K	0.00250	0.000694
Wall temperature, T_W, $^{\circ}$K	2500 and $2500\left(1 - \frac{2\epsilon}{5}\right)$	3000 and $3000\left(1 - \frac{\epsilon}{3}\right)$
Nozzle heat loss, $(P_Q)_{\epsilon=0}$, kw	2.0	1.5

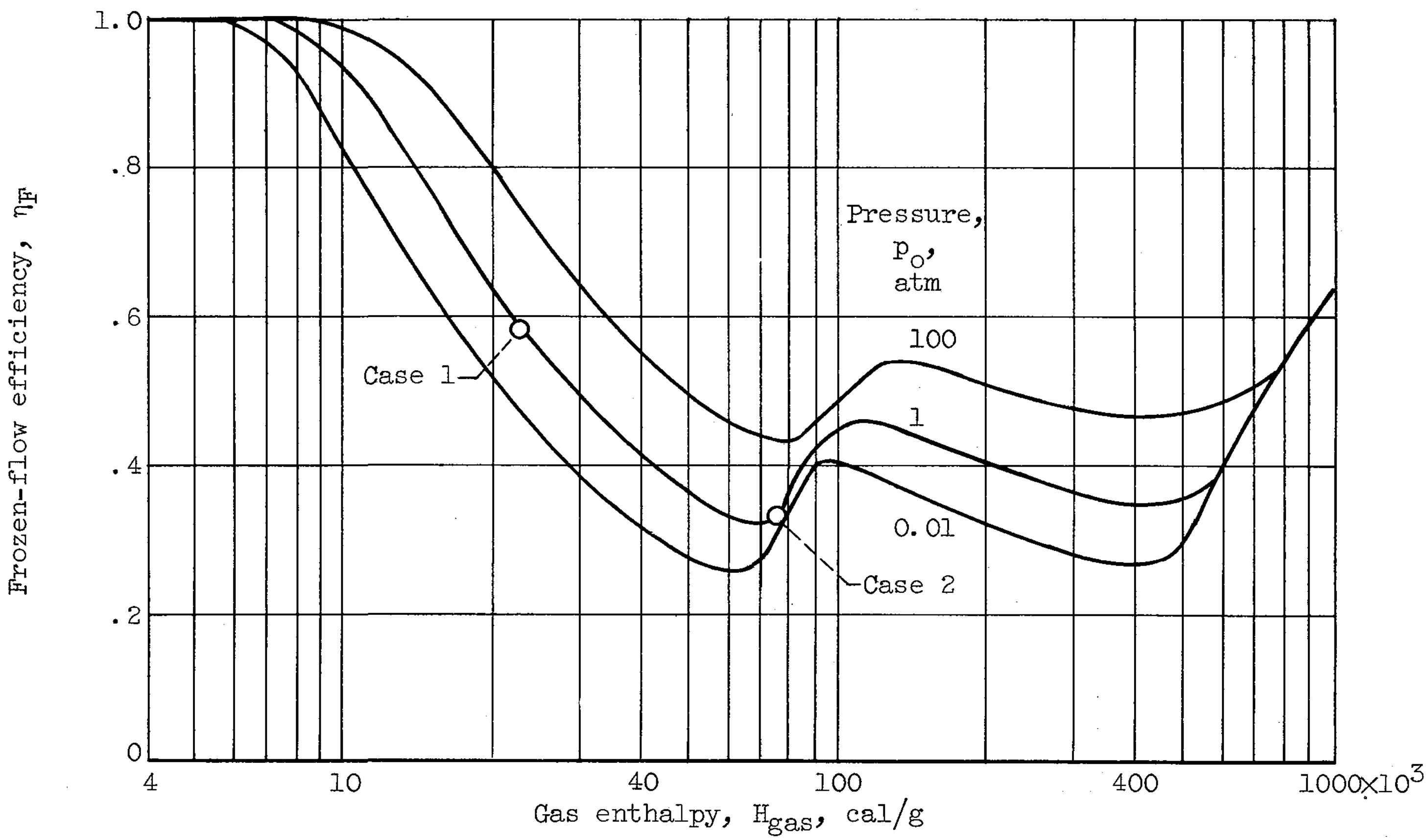

Figure 1. - Frozen-flow efficiency for hydrogen.

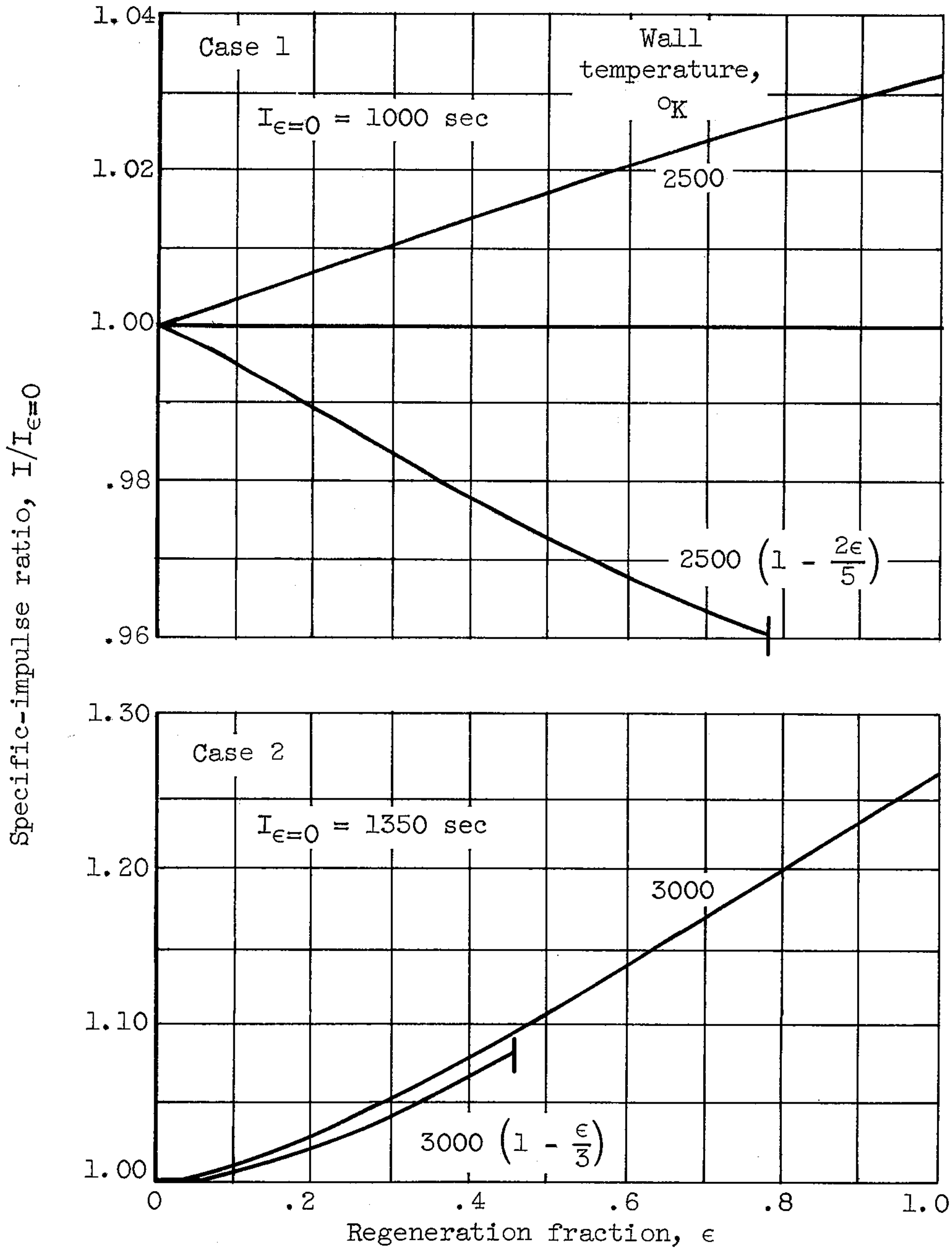

Figure 2. - Effect of regenerative cooling on thrustor performance.