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PERFORMANCE OF AN EHD POWER GENERATOR WITH A TWO-FLUID EJECTOR

by

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January 1981

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A detailed analysis and method of calculation is presented for determining the complete thermodynamic cycle of a two-fluid electrohydrodynamic (EHD) power generator. The analysis takes fully into account the compressibility of the media. Parameters are included which express the thermodynamic losses in the various components of the overall system. The severe restriction on output created by the electrical breakdown limit of the medium is clearly shown. The method for computing the net-electrical work output per unit mass of primary fluid and the net overall thermal efficiency of the system is carefully developed. A sample output together with the FORTRAN program are included.

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A detailed analysis and method of calculation is presented for determining the complete thermodynamic cycle of a two-fluid electrohydrodynamic (EHD) power generator. The analysis takes fully into account the compressibility of the media. Parameters are included which express the thermodynamic losses in the various components of the overall system. The severe restriction on output created by the electrical breakdown limit of the medium is clearly shown. The method for computing the net-electrical work output per unit mass of primary fluid and the net overall thermal efficiency of the system is carefully developed. A sample output together with the FORTRAN program are included.

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1. Background

This is the final report of the project "Study of Mark's Electrothermodynamic (ETD) Power Generator", sponsored by the Department of Energy (DOE). The primary objective of this effort has been to provide a detailed theoretical analysis of a type of electrohydrodynamic (EHD) power generator proposed by the Marks Polarized Corporation. Once a sound analytical basis was developed, it was possible to ascertain the limitations of the proposed system and to seek improvements.

The results of our first study are reported in detail in Ref. (1) and summarized more concisely in Ref. (2). That work indicated the originally proposed design would yield unacceptably poor performance and suggested a certain design revision. Further work was done to analyze such a design revision and is reported in the Appendix to Ref. (1). An improved simplified and shortened version of that work is reported in Ref. (3). Unfortunately, the new results indicated that the revised design, while showing somewhat improved performance, still would not appear sufficiently competitive in overall efficiency.

In the first study, some minor effects of compressibility of the medium were neglected. This was done in order to simplify the calculations. Also, it has been conjectured by Marks and others that it might be possible to improve greatly the performance of EHD-generators which utilizes an ejector by employing a two-fluid cycle. Finally, performance gains that a diffuser might bring about appeared worthy of study. To this end, a second study for a two-fluid cycle was undertaken in which a diffuser is introduced just prior to the EHD generator and where full account is taken of the compressibility of both fluids at all locations.

The principal earlier effort along the lines of our second study is Ref. (4), by Huberman, et. al, but our present work has gone beyond anything undertaken in Ref. (4). Although a two-fluid generator is analyzed in Ref. (4), including the compressibility of both fluids, Huberman et. al, make no attempt to study the complete thermodynamic cycle. There are, moreover, a number of questionable assumptions which cast serious doubt in the validity of the results given in Ref. (4).

The computational scheme that we have developed was reported in Ref. (5). There a methodical derivation of the working formulas is given together with some preliminary results. Some further results are given in Ref. (6).

The present report updates the material given in Refs (5) and (6). In particular, we have found that instead of writing an energy balance across the condenser, it is more convenient to use a momentum balance as shown in Section II of this report. We have reproduced herein the complete analysis in its latest version.

A sample calculation for the two-fluid system is also included together with the computer program listing.

Figure 1.1 is a schematic of the generator configuration studied. In Marks' design, the centerline of the channel, which is shown in Fig. 1.1 as a straight line, is curved sc as to form a closed loop.

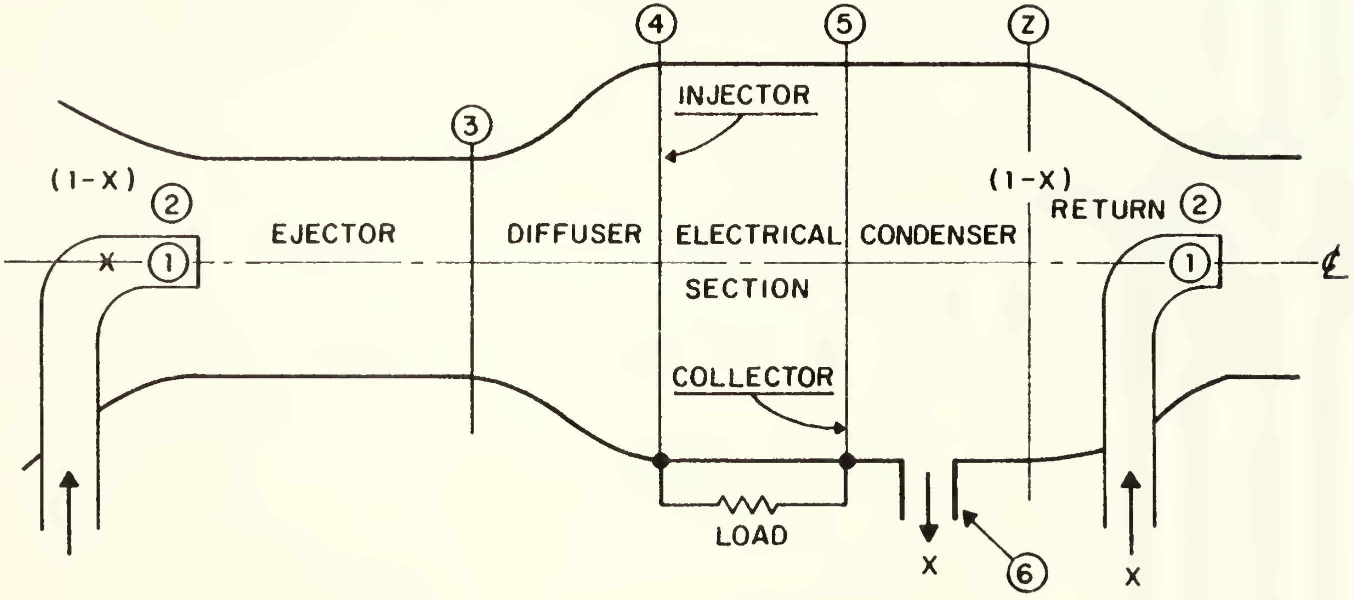

Fig. I.1 Schematic of Generator Configuration

2. Introduction

For purposes of analysis, the overall thermodynamic process in the two-fluid EHD generator may be represented by the schematic flow diagram shown in Fig. 2.1.

Primary fluid enters the ejector at station 1, secondary fluid enters at station 2 and the mixture leaves at station 3.

The mixture then passes through a diffuser, process 3→4, the basic purpose of which is to reduce the kinetic energy of the flow and thereby decrease the associated friction losses downstream of the diffuser. On the other hand the diffuser introduces certain losses of its own so that some care is necessary to optimize the design in this respect.

The gas mixture then passes through the electrical power section, process 4→5, from which the gross electrical power is extracted.

Finally, the gas mixture enters the condenser/separator at station 5. The primary fluid is separated from the gas mixture by condensation and leaves at station 6. The fluid at this point is assumed to be compressed liquid at a known static pressure P_6 and a known static temperature T_6 . Kinetic energy at station 6 is regarded as negligible. The secondary fluid leaves the condenser/separator and enters the ejector at station 2. We assume, moreover, that

$$P_6 = P_2 = P_1 \tag{2.1}$$

and

$$T_6 = T_2 \tag{2.2}$$

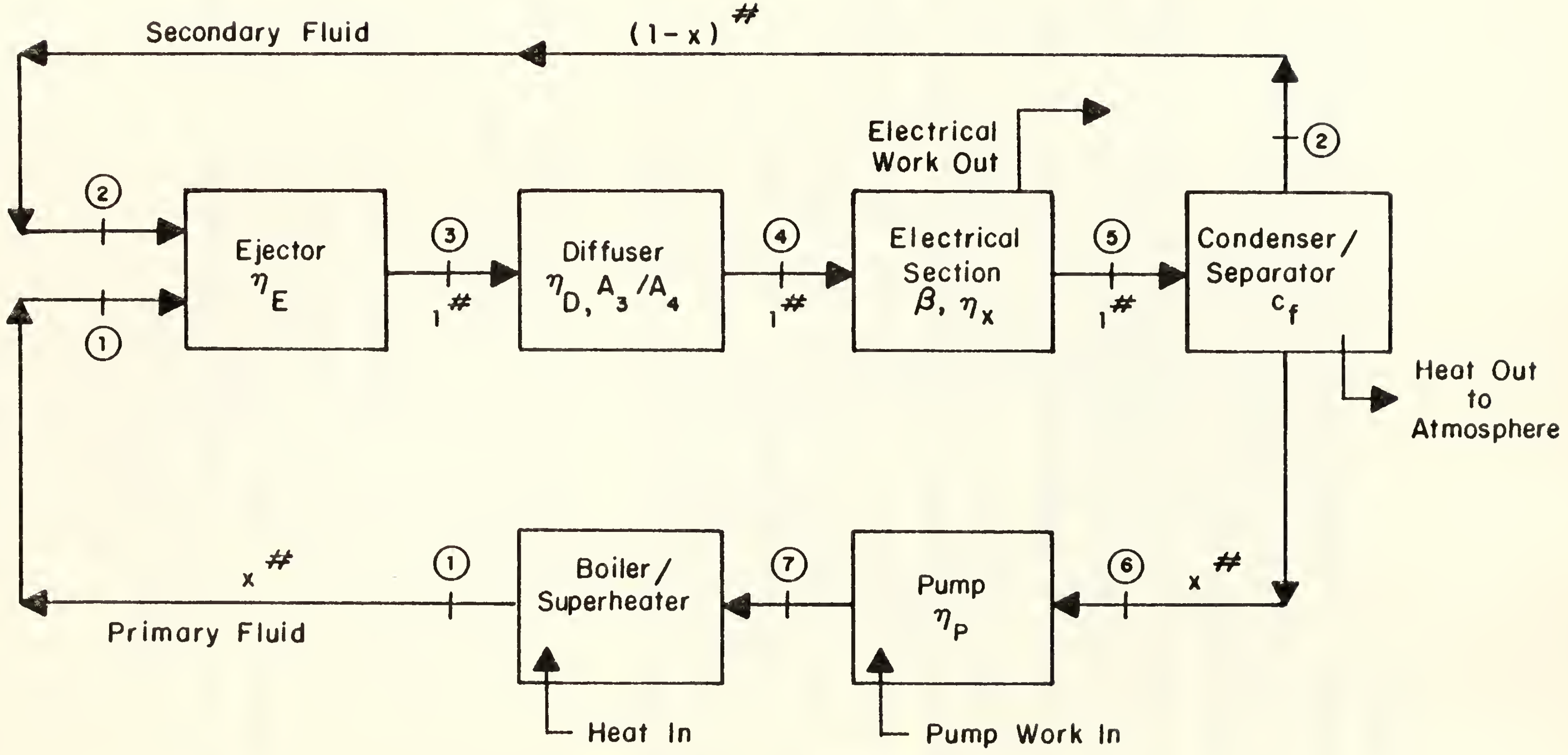

Fig.2.1 SCHEMATIC FLOW DIAGRAM OF TWO - FLUID EHD CYCLE.

The primary fluid which leaves the condenser/separator at station 6 is circulated back through the pump and through the boiler/superheater, process 7→1.

It should also be explained that the primary fluid at station 1 is a condensible vapor of high molecular weight which contains fine liquid droplets. Unless specifically stated otherwise the quality z at this location is taken as 0.95. The important thermodynamic static properties at station 1 can be expressed in the following form.

$$h_1 = h_f + z\, h_{fg} \quad \text{Enthalpy} \tag{2.3}$$

$$s_1 = s_f + z\, s_{fg} \quad \text{Entropy} \tag{2.4}$$

Here subscript f denotes the saturated liquid and subscript fg denotes the change between saturated liquid and saturated vapor. All properties are evaluated at a specified pressure P_1 ; the corresponding saturation temperature T_1 is then also known.

The corresponding stagnation properties T_{s1} and h_{s1} are fixed when the stagnation pressure P_{s1} is specified. Of course the entropy has the same value s_1 at the stagnation condition as at the corresponding static state. Thus specification of P_{s1} and s_1 suffices to fix all other stagnation properties.

While it is convenient to start the analyses by stipulating the quality at station 1, it is also advisable later in the calculation to determine the corresponding quality at station 4, the entrance to the electrical working section. It is essential that the fluid entering the working section contain finely dispersed liquid droplets of the proper size. These droplets carry the electrical charges that are the central feature of EHD power generation. We assume tentatively that acceptable droplet characteristics are obtained by maintaining the quality at the inlet to the working section in the range 0.92 to 0.98. These limits are only estimates.

The thermodynamic analysis would be greatly simplified if both fluids were perfect gases with constant specific heats. In fact only the secondary fluid satisfies this requirement. Nevertheless, we can define an "equivalent perfect gas" which adequately approximates the essential thermodynamic properties of the primary vapor/liquid mixture. When carried out judiciously, this procedure simplifies the analysis at the cost of only a small loss in numerical accuracy[7].

The ratio of specific heats γ of the "equivalent perfect gas" may be deduced from the important relation

$$(P_{s1}/P_1) = (T_{s1}/T_1)^{\gamma_1/(\gamma_1 - 1)} \tag{2.5}$$

Solving this for γ_1 gives

$$\gamma_1 = \left[1 - \frac{\ell n(T_{s1}/T_1)}{\ell n(P_{s1}/P_1)}\right]^{-1} \tag{2.6}$$

Another fundamental property of the "equivalent perfect gas" is its specific heat C_{p1} which may be evaluated from the expression

$$C_{p1} = \frac{(h_{s1} - h_1)}{(T_{s1} - T_1)} \tag{2.7}$$

where all quantities on the right are now known.

It then follows from standard perfect gas relations that the gas constant R_1 and the molecular weight W_1 of the "equivalent perfect gas" are, respectively,

$$R_1 = \left(\frac{\gamma_1 - 1}{\gamma_1}\right) C_{P1} \tag{2.8}$$

and

$$W_1 = \frac{\bar{R}}{R_1} \tag{2.9}$$

where $\bar{R}$ = universal gas constant

= 8317 joules/kg-mole ^{o}K

Eqs. (2.6) through (2.9) complete the definition of the "equivalent perfect gas" which adequately simulates the essential thermodynamic properties of the primary vapor/liquid mixture.

It should also be explained that the secondary fluid at station 2 is predominantly a noncondensing gas of low molecular weight primary vapor.

It can be shown that the mass ratio ω of condensible primary vapor to dry secondary gas at station 2 is given by the expression

$$\omega = \frac{W_V}{W_G} \frac{P_V(T_6)}{[P_2 - P_V(T_6)]} \tag{2.10}$$

where

W_v = true molecular weight of condensible vapor (not to be confused with the "equivalent molecular weight W_1" considered earlier)

W_G = molecular weight of noncondensing gas

$P_v(T_6)$ = vapor pressure of condensible primary fluid at known temperature T_6

P_2 = known static pressure at station 2

The present analysis is restricted to conditions under which ω is very small compared with unity and may be neglected. Thus the fluid at station 2 may be treated as dry gas. This greatly simplifies the analysis. Eq. (2.10) is useful for verifying that this assumption is indeed satisfied in any particular instance.

It should be added that if it later becomes of interest to make calculations for circumstances under which parameter ω is not negligible, the present analysis can in fact be generalized to include this effect. For the present, however, we prefer to deal only with the simpler situation in which ω may be neglected.

3. Ejector

The ejector receives a primary stream of high molecular weight gas at station 1, a secondary stream of low molecular weight gas at station 2 and discharges the resulting mixture at station 3. Static conditions at these three stations are designated by subscripts 1 , 2 , 3 . Stagnation conditions at the corresponding stations are designated by subscripts s1 , s2 and s3 .

The following quantities are arbitrarily specified or known at stations 1 and/or 2, namely,

Molecular weights: W_1 and W_2

Ratios of specific heats: γ_1 and γ_2

Stagnation pressure of primary jet: P_{s1}

Stagnation temperature of primary jet: T_{s1}

Static pressures: $P_1 = P_2$ $(= P_6)$

Static temperature of primary jet: T_1 (= saturation temperature of primary fluid at pressure P_1)

Static temperature of secondary jet: T_2 $(= T_6)$

Mass flow ratio: $\dot{m}_1/\dot{m}_3 = \dot{m}_1/(\dot{m}_1 + \dot{m}_2) = x$

Velocity ratio: $V_1/V_2 = y$

We treat the fluids at stations 1, 2, 3, 4 and 5 as perfect gases with constant specific heats.

The velocity ratio of the ejector may be developed as follows:

$$\frac{V_1}{V_2} = y = \frac{a_1}{a_2}\,\frac{M_1}{M_2} = \sqrt{\frac{\gamma_1\ R_1\ T_{s1}}{\gamma_2\ R_2\ T_2}}\ \frac{M_1}{\sqrt{T_{s1}/T_1}} \cdot \frac{1}{M_2} \qquad (3.1)$$

We can now use this result and other standard perfect gas relations to complete the calculation of key thermodynamic properties at stations 1 and 2. It is convenient to arrange these calculations sequentially as follows:

$$M_1 = \sqrt{\frac{2}{(\gamma_1 - 1)}\left(\frac{T_{s1}}{T_1} - 1\right)} \tag{3.2}$$

$$M_2 = \left(\frac{V_2}{V_1}\right)\sqrt{\frac{\gamma_1 \; R_1 \; T_{s1}}{\gamma_2 \; R_2 \; T_2}}\;\frac{M_1}{\sqrt{T_{s1}/T_1}} \tag{3.3}$$

$$\frac{T_{s2}}{T_2} = 1 + \frac{\gamma_2 - 1}{2}\;M_2{}^2 \tag{3.4}$$

$$T_{s2} = T_2 \; (T_{s2}/T_2) \tag{3.5}$$

$$\left(\frac{P_{s2}}{P_2}\right) = \left(\frac{T_{s2}}{T_2}\right)^{\frac{\gamma_2}{(\gamma_2 - 1)}} \tag{3.6}$$

$$P_{s2} = P_2 \left(\frac{P_{s2}}{P_2}\right) \tag{3.7}$$

Before we can determine the actual conditions at station 3, the outlet of the ejector, it is first necessary to analyze two other hypothetical cases as indicated schematically in Fig. 3.1. In all three of these cases the flow is taken as steady and adiabatic.

The first case, that shown in Fig. 3.1(a), involves a hypothetical device which receives two gas streams at stations 1 and 2 and discharges the resulting mixture at station x . Inlet conditions at 1 and 2 are identical to those of the actual ejector.

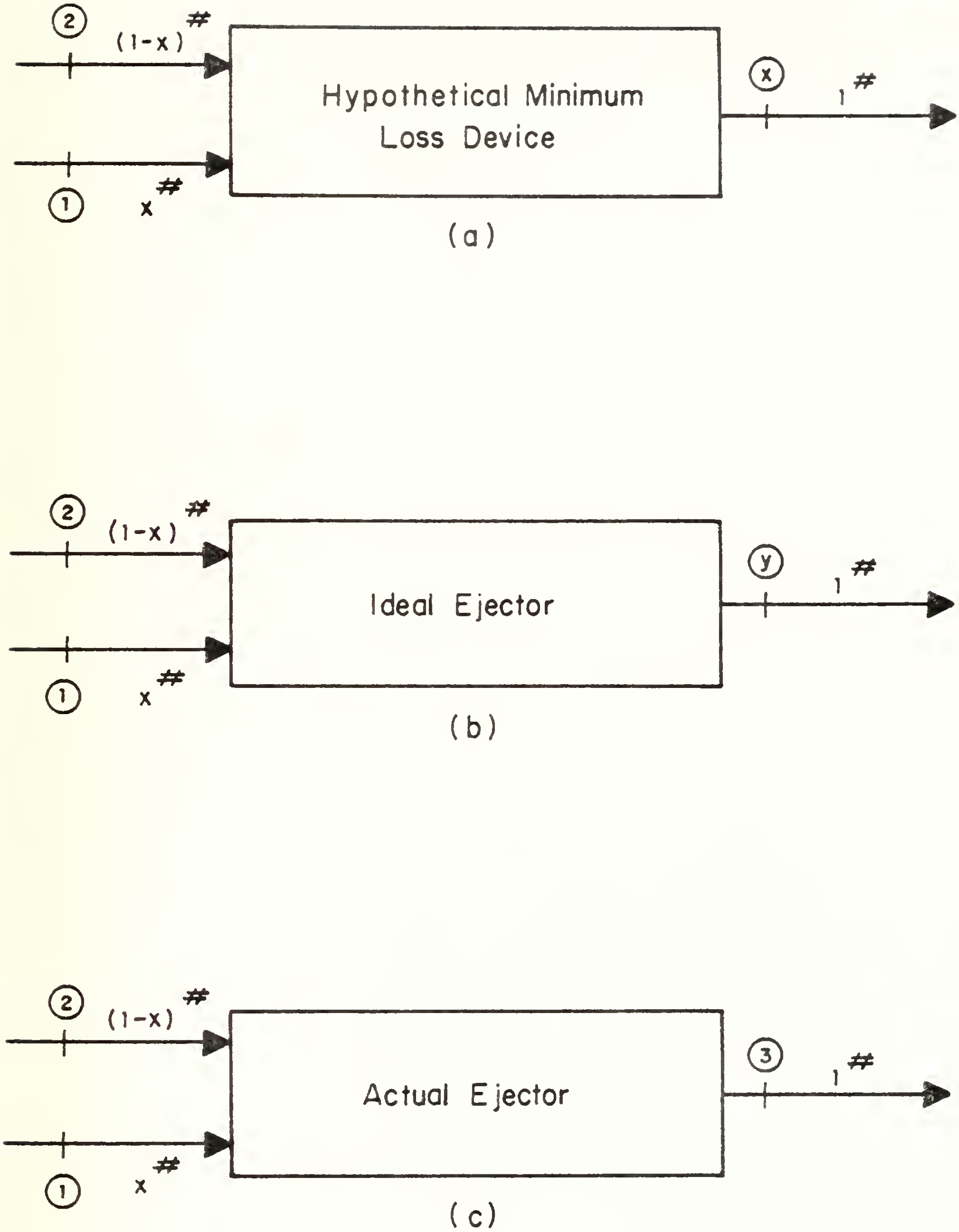

Fig. 3.1 COMPARISON OF ACTUAL EJECTOR WITH IDEAL EJECTOR AND WITH HYPOTHETICAL MINIMUM LOSS DEVICE.

Recall that the adiabatic mixing of two different gases is an inherently irreversible process that always involves a corresponding entropy increase. We stipulate that the first case is such that the only irreversibility which occurs is that associated with this mixing. We term this mass mixing to distinguish it from another type of mixing considered below which we term momentum mixing.

The second case, that shown in Fig. 3.1(b), involves an ideal ejector which receives two gas streams at stations 1 and 2 and discharges the resulting mixture at station y. Again, the inlet conditions at 1 and 2 are identical to those of the actual ejector. This case satisfies, among other relations, the idealized one-dimensional momentum equation for frictionless, constant area flow. It can be shown that in this case there is an overall entropy increase which includes not only the previously mentioned effect of mass mixing but also a further increase associated with momentum mixing.

The third case, that shown in Fig. 3.1(c), represents the actual ejector itself which receives input streams at stations 1 and 2 and which discharges the resulting mixture at station 3.

All three of the above cases refer to constant area processes in the sense that

$$A_x = A_y = A_3 = (A_1 + A_2) \qquad (3.8)$$

Once the hypothetical operating conditions at stations x and y have been found, it then becomes possible to express the corresponding actual conditions at station 3. This is accomplished through the use of an ejector effectiveness η_E . This parameter is defined more explicitly in the later analysis. Values of η_E must be estimated by reference to test data on ejectors (i.e., Ref. 8, 9, 10).

4. Adiabatic Mixing of Two Streams

The process in the ejector is treated as the adiabatic mixing of two streams. The following relations can be shown to apply.

$$\bar{R} = 8315 \quad \text{Joule/kg-mole } {}^{o}K \tag{4.1}$$

$$R_1 = \frac{\bar{R}}{W_1} \tag{4.2}$$

$$R_2 = \frac{\bar{R}}{W_2} \tag{4.3}$$

$$R_x = R_y = R_3 = x\, R_1 + (1 - x)\, R_2 \tag{4.4}$$

$$C_{p1} = \frac{\gamma_1\, R_1}{(\gamma_1 - 1)} \tag{4.5}$$

$$C_{p2} = \frac{\gamma_2\, R_2}{(\gamma_2 - 1)} \tag{4.6}$$

$$C_{px} = C_{py} = C_{p3} = x\, C_{p1} + (1 - x)\, C_{p2} \tag{4.7}$$

$$\gamma_x = \gamma_y = \gamma_3 = \frac{C_{p3}}{(C_{p3} - R_3)} \tag{4.8}$$

$$T_{sx} = T_{sy} = T_{s3} = \frac{1}{C_{p3}} [x\, C_{p1}\, T_{s1} + (1 - x)\, C_{p2}\, T_{s2}] \tag{4.9}$$

$$A_x = A_y = A_3 = (A_1 + A_2) \tag{4.10}$$

Notice that the quantities R , C_p , γ , T_s and A all have the same values at stations x, y and 3.

This fact may be used to simplify many of the subsequent expressions. It is always permissible to substitute subscript 3 for subscripts x or y on any of these quantities.

5. Mass Flow

It is convenient temporarily to omit station subscripts 1, 2, 3, x, y and thereby develop certain needed mass flow relations in generalized form. Thus the mass flow across an arbitrary station may be written and developed as follows.

$$\dot{m} = \rho AV = \left(\frac{P}{RT}\right) A \left(\sqrt{\gamma RT}\ M\right) = PAM\sqrt{\frac{\gamma}{RT}}$$

$$= \frac{P_s \cdot A}{\sqrt{RT_s/\gamma}} \; \frac{\sqrt{T_s/T}}{(P_s/P)} \; M \qquad (5.1)$$

This may be rewritten as

$$\dot{m} = \frac{P_s\ A}{\sqrt{RT_s/\gamma}} \; f(M) \qquad (5.2)$$

where the auxiliary function $f(M)$ is defined as follows.

$$f(M) = \frac{\sqrt{T_s/T}}{(P_s/P)} \; M = M \left[1 + \left(\frac{\gamma - 1}{2}\right) M^2\right]^{-\frac{(\gamma + 1)}{2(\gamma - 1)}} \qquad (5.3)$$

Eq. (5.2) can be applied specifically to stations 1, 2, x, y, 3 as follows

$$\dot{m}_1 = \frac{P_{s1}\ A_1}{\sqrt{R_1\ T_{s1}/\gamma_1}} \; f(M_1) \qquad (5.4)$$

$$\dot{m}_2 = \frac{P_{s2}\ A_2}{\sqrt{R_2\ T_{s2}/\gamma_2}} \; f(M_2) \qquad (5.5)$$

$$\dot{m}_x = \frac{P_{sx}\ A_3}{\sqrt{R_3\ T_{s3}/\gamma_3}}\ f(M_x) \tag{5.6}$$

$$\dot{m}_y = \frac{P_{sy}\ A_3}{\sqrt{R_3\ T_{s3}/\gamma_3}}\ f(M_y) \tag{5.7}$$

$$\dot{m}_3 = \frac{P_{s3}\ A_3}{\sqrt{R_3\ T_{s3}/\gamma_3}}\ f(M_3) \tag{5.8}$$

also

$$\left(\frac{\dot{m}_1}{\dot{m}_3}\right) = x \tag{5.9}$$

$$\dot{m}_x = \dot{m}_y = \dot{m}_3 = \dot{m}_1 + \dot{m}_2 \tag{5.10}$$

From Eqs. (5.4), (5.5), (5.9) and (5.10) we readily find that

$$\left(\frac{A_1}{A_2}\right) = \frac{x}{(1 - x)} \left(\frac{P_{s2}}{P_{s1}}\right) \sqrt{\frac{R_1\ T_{s1}\ \gamma_2}{R_2\ T_{s2}\ \gamma_1}}\ \frac{f(M_2)}{f(M_1)} \tag{5.11}$$

Then from Eq. (5.10) we infer also that

$$\left(\frac{A_1}{A_3}\right) = \frac{(A_1/A_2)}{(1 + A_1/A_2)} \tag{5.12}$$

Since all quantities on the right side of Eq. (5.11) are now known, Eqs. (5.11) and (5.12) fix the area ratios A_1/A_2 and A_1/A_3 .

From Eqs. (5.5), (5.6), (5.9), (5.10) and (3.8) we deduce further that

$$f(M_x) = \frac{(1 - A_1/A_3)}{(1 - x)} \left(\frac{P_{s2}}{P_{sx}}\right) \sqrt{\frac{R_3 \; T_{s3} \; \gamma_2}{R_2 \; T_{s2} \; \gamma_3}} \; f\,(M_2) \qquad (5.13)$$

All quantities on the right side of Eq. (5.13) except P_{sx} are now known. The method of determining P_{sx} is explained in a later section; refer to Eq. (5.15). Once P_{sx} has been found, Eq. (5.13) fixes $f(M_x)$ whereupon Eq. (5.3) fixes M_x itself. The solution of Eq. (5.3) for M when $f(M)$ is known involves an iterative procedure which is explained later in this section.

From Eqs. (5.6), (5.7), (5.8) and (5.10) we also find that

$$P_{sx} \; f(M_x) = P_{sy} \; f(M_y) = P_{s3} \; f(M_3) \qquad (5.14)$$

Assuming P_{sx} and M_x known, this relation along with Eq. (5.3) fixes P_{sy} when M_y is specified; it also fixes $f(M_3)$ and M_3 when P_{s3} is specified. The methods of calculating M_y and P_{s3} are explained later; refer to Eqs. (7.8) and (8.14).

Fig. 5.1 is a rough sketch of the function $f(M)$ as defined by Eq. (5.3). This function vanishes at $M = 0$ and at $M = \infty$. The maximum value occurs at $M = 1$ and equals

$$f_{max} = \left[\frac{2}{\gamma + 1}\right]^{\frac{(\gamma + 1)}{2(\gamma - 1)}} \qquad (5.15)$$

It is clear from the figure that in the range $0 < f < f_{max}$, Eq. (5.3) has two positive real roots, one subsonic and the other supersonic. Usually the supersonic root must be discarded because it is not consistent with a further constraint imposed by the second law of thermodynamics.

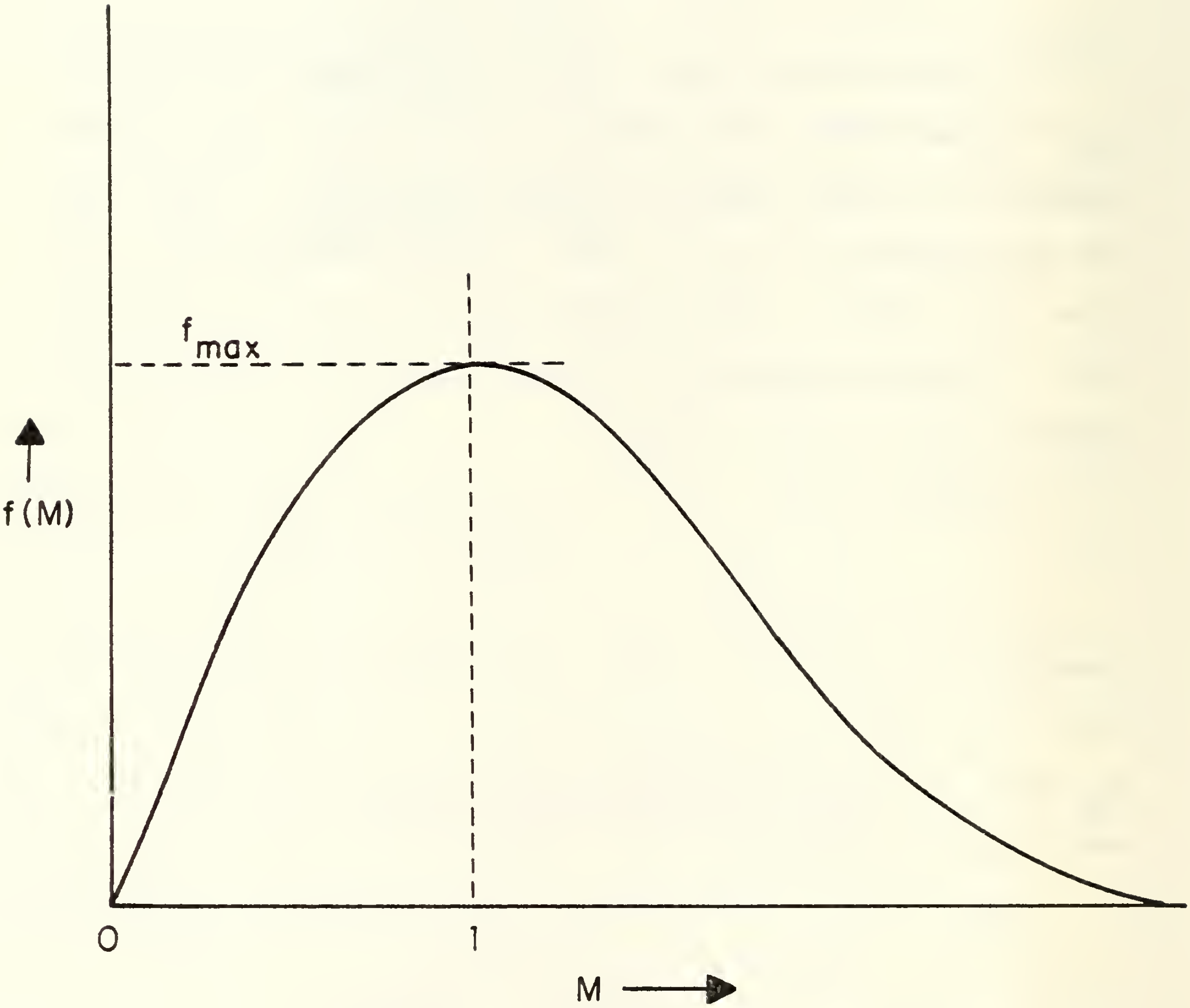

Fig. 5.1 APPROXIMATE SKETCH OF FUNCTION f(M)

In order to solve Eq. (5.3) for M when values of f and γ are specified, we utilize an iterative procedure based on Newton's method. Let M_n denote the nth trial value of M. We then define a function $F(M_n)$ and its derivative $F'(M_n)$ as follows.

$$F(M_n) = f\left[1 + \frac{\gamma - 1}{2} M_n^{\,2}\right]^{\frac{(\gamma + 1)}{2(\gamma - 1)}} - M_n \qquad (5.16)$$

$$F'(M_n) = f\left(\frac{\gamma + 1}{2}\right) M_n \left[1 + \left(\frac{\gamma - 1}{2}\right) M_n^{\,2}\right]^{\frac{(3 - \gamma)}{2(\gamma - 1)}} - 1 \qquad (5.17)$$

The $(n + 1)$st trial value of M may now be taken as

$$M_{(n + 1)} = M_n - \frac{F(M_n)}{F'(M_n)} \qquad (5.18)$$

The cycle of calculations defined by Eqs. (5.16), (5.17) and (5.18) is repeated until the result for M_n converges to a stable value at the desired level of accuracy.

Thus

$$M = \lim_{n \to \infty} M_n \qquad (5.19)$$

It is readily apparent that the value of M so obtained satisfies Eq. (5.3) for the prescribed values of f and γ.

6. Entropy

Consider the case shown in Fig. 3.1(a). The specific entropy s_x of the discharged gas may be expressed in the form

$$s_x = x\left[C_{p1}\,\ell n\left(\frac{T_x}{T_o}\right) - R_1\,\ell_n\left(\frac{P_{x1}}{P_o}\right)\right] + (1 - x)\left[C_{p2}\,\ell n\left(\frac{T_x}{T_o}\right) - R_2\,\ell_n\left(\frac{P_{x2}}{P_o}\right)\right] \tag{6.1}$$

where P_{x1} and P_{x2} are the partial pressures of the two components of the gas mixture. Symbols P_o and T_o denote the pressure and temperature of the ambient atmosphere. The entropy of each component is assigned the value zero at this reference state P_o , T_o .

Incidentally, the primary fluid, being condensible, might well exist only in the liquid state at the reference condition P_o , T_o . Nevertheless, so long as it is in the gaseous state at station x , Eq. (6.1) may still be used.

The partial pressures of the two components are proportional to the respective mol fractions. Hence

$$\left(\frac{P_{x1}}{P_o}\right) = \frac{x\,R_1}{x\,R_1 + (1 - x)R_2}\left(\frac{P_x}{P_o}\right) = \frac{x\,R_1}{R_3}\left(\frac{P_x}{P_o}\right) \tag{6.2}$$

$$\left(\frac{P_{x2}}{P_o}\right) = \frac{(1 - x)R_2}{x\,R_1 + (1 - x)R_2}\left(\frac{P_x}{P_o}\right) = \frac{(1 - x)R_2}{R_3}\left(\frac{P_x}{P_o}\right) \tag{6.3}$$

Upon substituting Eqs. (6.2) and (6.3) into (6.1) and simplifying we may obtain the result in the form

$$s_x = s_m + C_{p3} \ln \left(\frac{T_x}{T_o} \right) - R_3 \ln \left(\frac{P_x}{P_o} \right) \tag{6.4}$$

where

$$s_m = R_3 \ln R_3 - x R_1 \ln (x R_1) - (1 - x) R_2 \ln [(1 - x) R_2] \tag{6.5}$$

It can be shown that this quantity s_m represents the entropy increase associated with the mass mixing of the two different gases.

Moreover, since the entropy of the stagnation state s_x is by definition identical to that of the corresponding static state x , we may replace T_x and P_x in Eq. (6.4) by T_{sx} and P_{sx} , respectively. Thus we obtain

$$s_x = s_m + C_{p3} \ln \left(\frac{T_{sx}}{T_o} \right) - R_3 \ln \left(\frac{P_{sx}}{P_o} \right) \tag{6.6}$$

In previous studies of this series, we have considered only the special case in which the same fluid is employed for both the primary and secondary streams. In that case we have

$$R_1 = R_2 = R_3 = R \tag{6.7}$$

$$C_{p1} = C_{p2} = C_{p3} = C_p \tag{6.8}$$

$$\gamma_1 = \gamma_2 = \gamma_3 = \gamma \tag{6.9}$$

Moreover, in this special case there is no mass mixing, so that we must set

$$s_m = 0 \tag{6.10}$$

Consequently, Eq. (6.6) now simplifies to

$$s_x = 0 + C_p \ln\left(\frac{T_{sx}}{T_o}\right) - R \ln\left(\frac{P_{sx}}{P_o}\right) \tag{6.11}$$

Next reverting to the case of two different gases, let Δt denote a time interval during which unit mass crosses station x. During this same interval x units of mass cross station 1 and $(1 - x)$ units of mass cross station 2. The entropy which leaves across station x must equal the entropy which enters across stations 1 and 2 plus the entropy increase caused by the mass mixing. Thus

$$s_x = s_m + x\, s_1 + (1 - x) s_2 \tag{6.12}$$

where

$$s_1 = C_{p1} \ln\left(\frac{T_{s1}}{T_o}\right) - R_1 \ln\left(\frac{P_{s1}}{P_o}\right) \tag{6.13}$$

$$s_2 = C_{p2} \ln\left(\frac{T_{s2}}{T_o}\right) - R_2 \ln\left(\frac{P_{s2}}{P_o}\right) \tag{6.14}$$

Upon eliminating s_x between Eqs. (6.6) and (6.12), we find that s_m also cancels from the result. It is then a simple matter to solve for the exit stagnation pressure in the form

$$\ln\left(\frac{P_{sx}}{P_o}\right) = \frac{1}{R_3}\left\{C_{p3} \ln\left(\frac{T_{s3}}{T_o}\right) - x\, s_1 - (1 - x) s_2\right\} \tag{6.15}$$

Thus the sequence defined by Eqs. (6.13), (6.14) and (6.15) now fixes P_{sx}. Next referring back to Eq. (5.13), we can calculate the value of $f(M_x)$; finally, from Eqs. (5.16), (5.17), (5.18) we can calculate M_x itself. Once P_{sx}, $T_{sx} = T_{s3}$ and M_x are known, it is a simple matter to calculate the corresponding conditions P_x, T_x from the usual perfect gas relations.

7. Momentum

Consider the idealized one dimensional constant area ejector shown in Fig. 3.1(b). The momentum equation for this system may be written

$$(P_1 + \rho_1 V_1^2) A_1 + (P_2 + \rho_2 V_2^2) A_2 = (P_y + \rho_y V_y^2) A_y \tag{7.1}$$

The mass conservation relation for this system can be expressed in the form

$$\frac{\rho_1 A_1 V_1}{x} = \frac{\rho_2 A_2 V_2}{(1 - x)} = \rho_y A_y V_y \tag{7.2}$$

Let us divide the three terms of Eq. (7.1) by the corresponding three terms of Eq. (7.2). Notice that the areas cancel out of the result. In this way we obtain

$$x \frac{(P_1 + \rho_1 V_1^2)}{\rho_1 V_1} + (1 - x) \frac{(P_2 + \rho_2 V_2^2)}{\rho_2 V_2} = \frac{(P_y + \rho_y V_y^2)}{\rho_y V_y} \tag{7.3}$$

Temporarily dropping the station subscript, we next develop the typical term of Eq. (7.3) in generalized format as follows.

$$\frac{(P + \rho V^2)}{\rho V} = \frac{\left[P + \frac{P}{RT} (\gamma RT) M^2\right]}{\frac{P}{RT} \sqrt{\gamma RT}\, M} = \sqrt{\frac{RT_s}{\gamma}}\, \frac{(1 + \gamma M^2)}{M \sqrt{T_s/T}}$$

$$= \sqrt{\frac{RT_s}{\gamma}}\, \frac{(1 + \gamma M^2)}{M \sqrt{1 + (\frac{\gamma - 1}{2}) M^2}} \tag{7.4}$$

Observe that the pressure P cancels from the result.

It is convenient to define the auxiliary function

$$g(M) = \frac{M}{(1 + \gamma M^2)} \sqrt{1 + (\frac{\gamma - 1}{2}) M^2} \qquad (7.5)$$

With this notation Eq. (7.3) may be rewritten in the form

$$\frac{x}{g(M_1)} \sqrt{\frac{R_1 \; T_{s1}}{\gamma_1}} + \frac{(1 - x)}{g(M_2)} \sqrt{\frac{R_2 \; T_{s2}}{\gamma_2}} = \frac{1}{g(M_y)} \sqrt{\frac{R_3 \; T_{s3}}{\gamma_3}} \qquad (7.6)$$

Rearranging gives

$$g(M_y) = \sqrt{\frac{R_3 \; T_{s3}}{\gamma_3}} \left\{ \frac{x}{g(M_1)} \sqrt{\frac{R_1 \; T_{s1}}{\gamma_1}} + \frac{(1 - x)}{g(M_2)} \sqrt{\frac{R_2 \; T_{s2}}{\gamma_2}} \right\}^{-1} \qquad (7.7)$$

Since all quantities on the right are known, Eq. (7.7) fixes $g(M_y)$. Then M_y itself can be found by inverting Eq. (7.5). Fortunately, an explicit solution is possible in this case as Eq. (7.5) can be reduced to a quadratic in M^2 . The result is

$$M^2 = \frac{(1 - 2\gamma g^2) \pm \sqrt{1 - 2(\gamma + 1) g^2}}{1 - \gamma(1 - 2\gamma g^2)} \qquad (7.8)$$

The general character of the function $g(M)$ is sketched in Fig. 7.1. Notice that $g(M)$ vanishes at $M = 0$, reaches its peak value g_{max} at $M = 1$, and decreases toward the limit g_∞ as $M \to \infty$. It can be shown that

$$g_{max} = \frac{1}{\sqrt{2(\gamma + 1)}} \qquad (7.9)$$

$$g_\infty = \frac{1}{\gamma} \sqrt{\frac{(\gamma - 1)}{2}} \qquad (7.10)$$

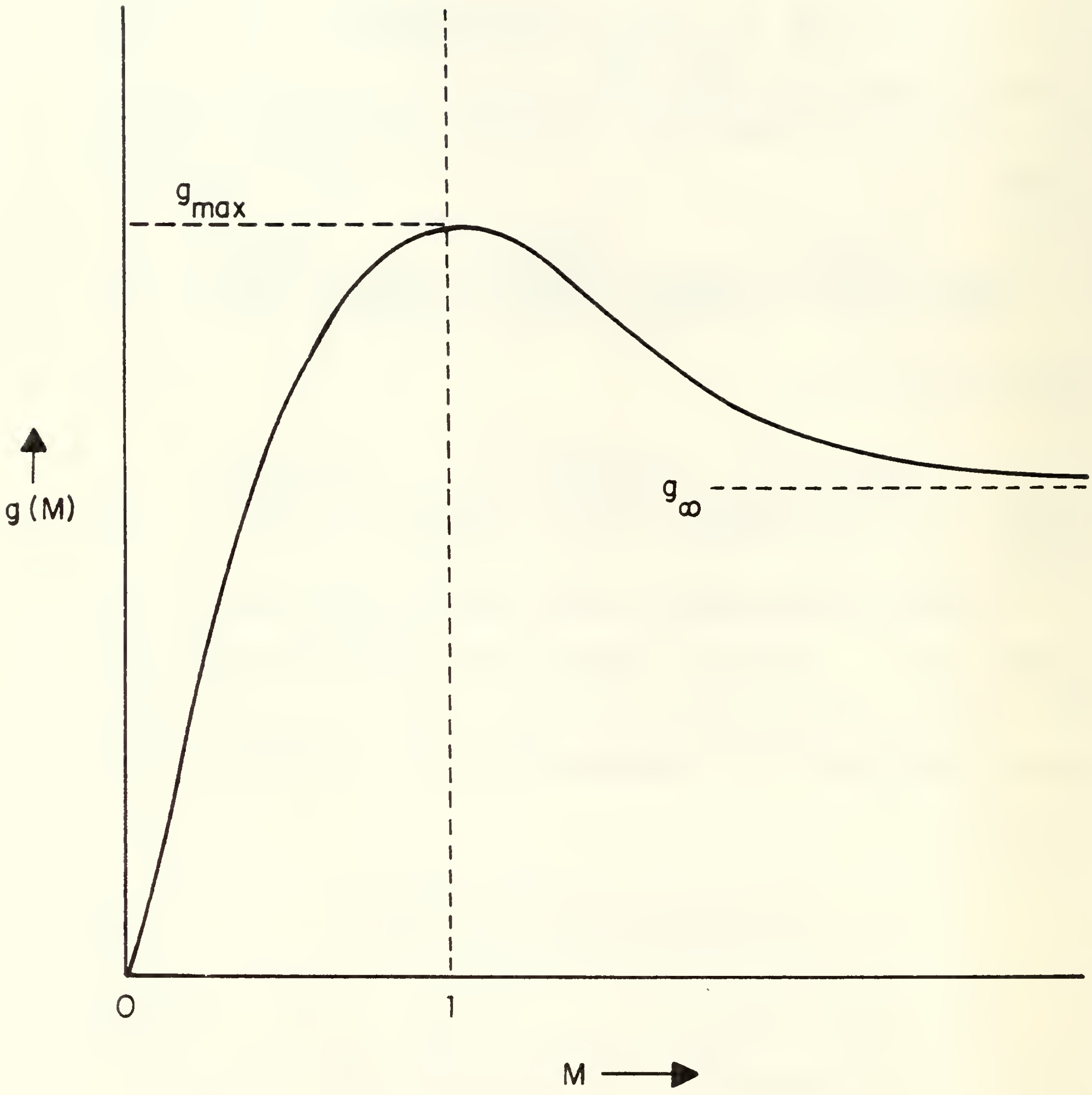

Fig. 7.1 APPROXIMATE SKETCH OF FUNCTION g(M)

Fig. 7.1 discloses the existence of a supersonic root over the range $g_\infty < g < g_{max}$. This root should not be accepted until a check calculation is made to determine whether the result is consistent with the second law of thermodynamics. The subsonic root is found by retaining only the negative sign before the radical in Eq. (7.8).

Once M_y has been found from Eq. (7.8), the corresponding value of P_{sy} may be found from Eqs. (5.3) and (5.14). This suffices to fix all properties at states y and sy.

8. Availability

The entropies s_1 and s_2 of the two input streams were defined earlier in Eqs. (6.13) and (6.14). The corresponding steady flow availability functions with respect to an ambient atmosphere at pressure P_o and temperature T_o may be written

$$\psi_1 = C_{p1} (T_{s1} - T_o) - T_o s_1 \tag{8.1}$$

$$\psi_2 = C_{p2} (T_{s2} - T_o) - T_o s_1 \tag{8.2}$$

Consequently the total available energy entering the system becomes

$$\psi_m = x \psi_1 + (1 - x)\psi_2 \tag{8.3}$$

The respective entropies of the streams leaving at stations x , y and 3 are

$$s_x = s_m + C_{p3} \ln \left(\frac{T_{s3}}{T_o}\right) - R_3 \ln \left(\frac{P_{sx}}{P_o}\right) \tag{8.4}$$

$$s_y = s_m + C_{p3} \ln \left(\frac{T_{s3}}{T_o}\right) - R_3 \ln \left(\frac{P_{sy}}{P_o}\right) \tag{8.5}$$

$$s_3 = s_m + C_{p3} \ln \left(\frac{T_{s3}}{T_o}\right) - R_3 \ln \left(\frac{P_{s3}}{P_o}\right) \tag{8.6}$$

where s_m has been previously defined in Eq. (6.5).

The corresponding availabilities of the streams leaving at stations x, y and 3 may therefore be written

$$\psi_x = C_{p3}\ (T_{s3} - T_o) - T_o\ s_x \qquad (8.7)$$

$$\psi_y = C_{p3}\ (T_{s3} - T_o) - T_o\ s_y \qquad (8.8)$$

$$\psi_3 = C_{p3}\ (T_{s3} - T_o) - T_o\ s_3 \qquad (8.9)$$

Now consider the losses of availability listed below. By substituting the above expressions for the quantities on the left and simplifying we readily obtain the expressions shown on the right. Thus

$$(\psi_m - \psi_x) = T_o\ s_m \qquad (8.10)$$

$$(\psi_x - \psi_y) = R_3\ T_o\ \ell n \left(\frac{P_{sx}}{P_{sy}}\right) \qquad (8.11)$$

$$(\psi_x - \psi_3) = R_3\ T_o\ \ell n \left(\frac{P_{sx}}{P_{s3}}\right) \qquad (8.12)$$

These results are very significant. Eq. (8.10) defines the loss of available energy caused by the mass mixing of the two different gases. Eq. (8.11) defines the further loss of available energy caused by the momentum mixing in an idealized ejector. Eq. (8.12) defines the augmented loss of available energy caused by the momentum mixing in the real ejector.

It is useful to postulate an empirical relation between these last two losses which is shown below on the left. The expression on the right then follows from Eqs. (8.11) and (8.12). Thus

$$\frac{(\psi_x - \psi_y)}{(\psi_x - \psi_3)} = \eta_E = \frac{\ell n\ (P_{sy}/P_{sx})}{\ell n\ (P_{s3}/P_{sx})} \qquad (8.13)$$

We term η_E the ejector effectiveness. Its value, which is always less than unity, must be estimated from appropriate test data on ejectors.

If we treat η_E as known, Eq. (8.13) fixes P_{s3}. The solution is simply

$$P_{s3} = P_{sx} \left(\frac{P_{sy}}{P_{sx}} \right)^{\frac{1}{\eta_E}} \tag{8.14}$$

We can next find $f(M_3)$ from Eq. (5.14) and M_3 from Eqs. (5.16), (5.17) and (5.18). This suffices to fix all properties at states 3 and s3 thereby completing the analysis of the ejector.

9. Diffuser

It is convenient to analyze the diffuser in terms of the concept of availability in steady flow. However, we wish to deal with the characteristics of the diffuser itself and these cannot depend on the arbitrary values P_o , T_o which happen to characterize the condition of the ambient atmosphere. We can achieve our objective by defining the availability with respect to a reference state P_3 , T_3 which characterizes the diffuser rather than with respect to the ambient state P_o , T_o .

Under these circumstances we may write the appropriate availabilities at diffuser inlet and outlet as follows

$$\psi_{s3} = C_{p3} (T_{s3} - T_3) - T_3 \left\{ C_{p3} \ln\left(\frac{T_{s3}}{T_3}\right) - R_3 \ln\left(\frac{P_{s3}}{P_3}\right)\right\} \quad (9.1)$$

$$\psi_{s4} = C_{p3} (T_{s3} - T_3) - T_3 \left\{ C_{p3} \ln\left(\frac{T_{s3}}{T_3}\right) - R_3 \ln\left(\frac{P_{s4}}{P_3}\right)\right\} \quad (9.2)$$

These equations make use of the fact that $T_{s4} = T_{s3}$. Also, states s3 and 3 are at the same entropy so that

$$(s_{s3} - s_3) = 0 = C_p \ln\left(\frac{T_{s3}}{T_3}\right) - R_3 \ln\left(\frac{P_{s3}}{P_3}\right) \quad (9.3)$$

From Eqs. (9.1) and (9.3) we conclude that

$$\psi_{s3} = C_{p3} (T_{s3} - T_3) = \left(\frac{V_3^{\,2}}{2}\right) \quad (9.4)$$

This result shows that the available energy at the diffuser inlet is simply the inlet kinetic energy itself.

The loss of availability through the diffuser may be found by subtracting Eq. (9.2) from (9.1). The result is

$$(\psi_{s4} - \psi_{s3}) = \Delta\psi = + R_3 T_3 \ell n \left(\frac{P_{s3}}{P_{s4}} \right) \tag{9.5}$$

We now define the diffuser effectiveness as

$$\left(\frac{\psi_{s4}}{\psi_{s3}} \right) = \eta_D \tag{9.6}$$

so that

$$\left(\frac{\psi_{s3} - \psi_{s4}}{\psi_{s3}} \right) = \frac{\Delta\psi}{\psi_{s3}} = (1 - \eta_D) = \frac{R_3 T_3 \ell n \left(\frac{P_{s3}}{P_{s4}} \right)}{C_{p3} (T_{s3} - T_3)} \tag{9.7}$$

This reduces readily to

$$(1 - \eta_D) = \frac{\ell n \left(\frac{P_{s3}}{P_{s4}} \right)}{\left(\frac{\gamma_3 M_3^2}{2} \right)} \tag{9.8}$$

Solving for the pressure ratio gives

$$\frac{P_{s4}}{P_{s3}} = e^{- (1 - \eta_D) \frac{\gamma_3 M_3^2}{2}} \tag{9.9}$$

This is the result required. It fixes P_{s4} when P_{s3}, M_3 and η_D are specified.

Assuming the area ratio A_3/A_4 to be arbitrarily specified, we can find M_4 from the continuity relation. Referring to Eq. (5.8) we may write

$$\dot{m}_3 = \frac{P_{s3} \; A_3}{\sqrt{R_3 \; T_{s3}/\gamma_3}} \; f(M_3) = \frac{P_{s4} \; A_4}{\sqrt{R_3 \; T_{s3}/\gamma_3}} \; f(M_4) = \dot{m}_4 \tag{9.10}$$

Consequently

$$f(M_4) = \left(\frac{P_{s3}}{P_{s4}}\right)\left(\frac{A_3}{A_4}\right) f(M_3) \tag{9.11}$$

Eq. (9.11) fixes $f(M_4)$. Then M_4 follows in the usual way from Eqs. (5.16), (5.17) and (5.18). The result suffices to fix all properties at states 4 and s4. Thus

$$\left(\frac{T_{s3}}{T_4}\right) = \left(\frac{T_{s4}}{T_4}\right) = 1 + \left(\frac{\gamma_3 - 1}{2}\right) M_4^{\;2} \tag{9.12}$$

$$T_4 = T_{s3}/(T_{s3}/T_4) \tag{9.13}$$

$$\left(\frac{P_{s4}}{P_4}\right) = \left(\frac{T_{s3}}{T_4}\right)^{\frac{\gamma_3}{(\gamma_3 - 1)}} \tag{9.14}$$

$$P_4 = P_{s4}/(P_{s4}/P_4) \tag{9.15}$$

The configurations studied in earlier work did not incorporate a diffuser. For the purpose of comparing the results of the present analysis with corresponding earlier work, it is desirable to be able to eliminate the effects of the diffuser in certain cases. This can be accomplished in the present analysis simply by setting

$$\eta_D = 1 \tag{9.16}$$

and

$$\left(\frac{A_3}{A_4}\right) = 1 \tag{9.17}$$

It is easy to confirm that under these circumstances

$$T_{s4} = T_{s3} \tag{9.18}$$

$$P_{s4} = P_{s3} \tag{9.19}$$

$$M_4 = M_3 \tag{9.20}$$

$$A_4 = A_3 \quad \text{etc.} \tag{9.21}$$

and all diffuser effects disappear.

10. Electrical Power Section

The power conversion process in an EHD duct is usually treated on the basis either of constant area or of constant static state. Inasmuch as electrical power output per unit mass is small, the numerical differences between the results computed by these two methods is negligible. For definiteness in this analysis, however, we assume constant area.

The electrical power that can be obtained from an EHD duct of constant area, negligible change of density and optimum length can be estimated from the one dimensional version of Poisson's equation which governs the electrical field. The solution is well known and will not be derived here; a detailed derivation may be found in Ref. (3). The essential result may be written in the form

$$P_e = \frac{1}{2} \varepsilon E_b^2 A_4 V_4 \tag{10.1}$$

where

P_e = gross electric power output, watts

ε = permittivity of medium

= 8.854×10^{-12} farad/m (for any gas)

E_b = dielectric strength of medium, volts/m

A_4 = area of duct (constant)

V_4 = velocity

According to the test data analyzed in Ref. 4, the dielectric strength is well approximated by the expression

$$E_b = C_{B3} R_3 \rho_4 \tag{10.2}$$

where C_{B3} is a characteristic constant of the medium. The data show that Eq. (10.2) applies to air or steam up to about 10 atmospheres pressure with

$$C_{B3} \doteq 9.49 \times 10^3 \ m^2 \ {}^\circ K/cmb \tag{10.3}$$

In this study we assume that Eq. (10.2) can be extrapolated up to about 100 atmospheres pressure. We also assume that an expression of the same form applies to other media besides air or steam but that each medium has its own characteristic value of the breakdown constant C_B.

In the two-fluid system, the separate values of the breakdown constants C_{B1} and C_{B2} are usually known, but the breakdown constant C_{B3} of the resulting mixture is seldom known. In the absence of adequate test data bearing on this point, we tentatively assume that C_{B3} can be estimated from the hypothetical relation

$$C_{B3} = \frac{1}{R_3} [x R_1 C_{B1} + (1 - x) R_2 C_{B2}] \tag{10.4}$$

Upon substituting Eq. (10.2) into (10.1) and dividing through by the mass flow rate, we find the electrical work output per unit mass of fluid in the form:

$$\frac{P_e}{\dot{m}_4} = \left(\frac{\varepsilon \ C_{B3}^2 \ R_3^2}{2} \right) \rho_4 = C_{p3} \ (T_{s4} - T_{s5}) \tag{10.5}$$

By use of standard perfect gas relations, Eq. (10.5) can be changed to a more useful form. In this connection set

$$(T_{s4} - T_{s5}) = \Delta T_s \tag{10.6}$$

and

$$\beta = \frac{\varepsilon \, C_{B3}^2 \, P_o}{T_o^2} \tag{10.7}$$

where

P_o = ambient pressure, N/m^2

T_o = ambient temperature, °K

Notice that β represents a dimensionless version of the electrical breakdown constant.

Eq. 10.5 now yields the important result

$$\frac{\Delta T_s}{T_{s4}} = \beta \left(\frac{\gamma_3 - 1}{2\gamma_3}\right)\left(\frac{P_{s4}}{P_o}\right)\left(\frac{T_o}{T_{s4}}\right)^2 \left(1 + \left(\frac{\gamma_3 - 1}{2}\right) M_4^2\right)^{-\frac{1}{\gamma_3 - 1}} \tag{10.8}$$

The corresponding gross electrical work output per unit mass of fluid is then simply

$$W_e^* = C_{P3} \, \Delta T_s \tag{10.9}$$

Unfortunately, the known value of ε and the typical experimentally measured values of C_B are very small. Consequently, the dimensionless breakdown constant β is extremely small compared to unity. Hence the drop in stagnation temperature ΔT_s and the gross electrical work per unit mass W^*_e are also typically very small. This is a very basic and serious limitation on the performance that can be obtained from an EHD generator.

Treating the process 4→5 as isentropic, we may write

$$P_{s5} = P_{s4} \left(\frac{T_{s5}}{T_{s4}}\right)^{\frac{\gamma_3}{(\gamma_3 - 1)}} \tag{10.10}$$

By analogy with Eq. (5.8) we write the continuity relation as

$$\dot{m}_4 = \frac{P_{s4}\ A_4}{\sqrt{R_3\ T_{s4}/\gamma_3}}\ f(M_4) = \frac{P_{s5}\ A_5}{\sqrt{R_3\ T_{s5}/\gamma_3}}\ f(M_5) = \dot{m}_5 \tag{10.11}$$

It then follows that

$$f(M_5) = \sqrt{\frac{T_{s5}}{T_{s4}}} \left(\frac{P_{s4}}{P_{s5}}\right) f(M_4) \tag{10.12}$$

This fixes $f(M_5)$ whereupon M_5 may be found in the usual way from Eqs. (5.16), (5.17) and (5.18). However, convergence should now be very rapid since we may take as a first approximation

$$M_5 \approx M_4 \tag{10.13}$$

This solution now suffices to fix all properties at states 4 and s4 .

11. Condenser/Separator

The primary fluid which leaves the condenser/separator at station 6 is assumed to be compressed liquid at known static pressure $P_6 = P_2 = P_1$ and at known static temperature $T_6 = T_2$. The kinetic energy of the liquid at station 6 is assumed to be negligible.

Temperature T_6 must be equal to or greater than the ambient temperature T_o in order to satisfy the requirements of a heat balance on the condenser/separator. No attempt is made in this analysis to formulate this actual heat balance; instead T_6 is simply treated as a given or known quantity. However, it may be of interest later to investigate the effects of varying T_6 on the overall performance of the EHD system.

The secondary fluid which leaves the condenser/separator at station z consists primarily of a low molecular weight noncondensing gas. It also contains some secondary vapor, but the mass fraction of this vapor is treated as negligible in this analysis. Thus the secondary fluid at station z is treated as dry gas.

The thermodynamic process in the condenser/separator can be most conveniently analyzed and modelled by employing the momentum theorem. We treat the condenser/separator essentially as a one dimensional, constant area device in steady flow. By equating the net applied pressure and drag forces to the change of momentum flux in the direction of flow, we obtain the following simple relation, namely,

$$(p_5 - p_z)A_5 - D = (1 - x)\dot{m}_3V_z - \dot{m}_3V_5 \qquad (11.1)$$

The effective drag force D in this equation represents two irreversible momentum loss effects. One of these is the loss of momentum produced when the condensible vapor in the incoming flow is condensed and brought to a halt on the stationary surfaces of the condenser/separator. The other is the additional friction drag force; the latter is conveniently expressed in terms of an empirical friction coefficient c_f . Thus we may write

$$D = x\,\dot{m}_3V_5 + c_f(\tfrac{1}{2}p_5V_5{}^2)A_5 \qquad (11.2)$$

Next we substitute Eq. (11.2) into 11.1), bring all terms to one side of the equation, regroup terms, and divide through by the quantity p_5A_5 . We also make use of the following auxiliary relationships, namely,

$$\frac{p_5V_5^2A_5}{p_5A_5} = \frac{\dot{m}_3V_5}{p_5A_5} = \gamma_3M_5^2 \qquad (11.3)$$

and

$$\frac{\dot{m}_3V_z}{p_5A_5} = \gamma_3M_5M_z \quad \frac{\gamma_2R_2T_z}{\gamma_3R_3T_5} \qquad (11.4)$$

In this way the following result is finally obtained -

$$E(x) = (1 - \frac{p_z}{p_5}) + (1 - x - \frac{c_f}{2})\gamma_3M_5^2 - (1 - x)M_5M_z\sqrt{\frac{\gamma_2R_2T_z}{\gamma_3R_3T_5}} = 0 \qquad (11.5)$$

The quantity $E(x)$ serves here merely as a convenient abbreviation for the sum of terms shown. It may be said to represent an excess of momentum available over that required to satisfy the various losses that occur across the condenser/separator. In any case, for assigned values of all other parameters, we seek by successive trials a value of x such that $E(x) = 0$. Thus Eq. (11.5) fixes the mass fraction x in a manner which is consistent with the other specified input parameters.

Of course, if the various fixed input parameters are not suitably chosen, Eq. (11.5) cannot be satisfied for any trial value of x in the range $0 < x < 1$, and no solution is physically possible under these conditions.

12. Cycle Efficiency

Once a solution has been found such that $E(x) = 0$, it becomes a straightfoward matter to calculate the corresponding overall cycle efficiency.

Because of the pressure drop through the boiler/superheater, the pressure $P_7 = P_{s7}$ at boiler inlet is slightly higher than the stagnation pressure P_{s1} of the primary fluid at the ejector inlet. We assume that the ratio P_{s1}/P_{s7} is a specified constant. Hence with P_{s1} specified, P_{s7} is also known. Also the pressures $P_6 = P_1$ are known.

Consider the ideal pump work w_p^* done per unit mass of primary fluid. For the present consider the hypothetical case of a reversible pump. Also note that density changes across the pump are negligible. Hence we may write

$$w_p^* = \frac{(P_{s7} - P_6)}{\rho_6} \tag{12.1}$$

The ideal gross electrical work output per unit mass of mixed fluid has earlier been established in Eq.(10.5). It is denoted by symbol w_e^*.

Let us now denote the net useful electrical work output per unit mass of primary fluid by symbol w_{net}. It may be related to w_e^* and w_p^* in the following way

$$w_{net} = \left(\frac{\eta_x w_e^*}{x} - \frac{w_p^*}{\eta_p}\right) \quad \text{Joule/kg} \tag{12.2}$$

where η_x, the excitation efficiency, allows for the small electrical power expended to excite the system and where η_p, the pump efficiency, allows for irreversibilities in the pump.

The heat input in the boiler/superheater per unit mass of primary fluid may be written

$$q_{in} = (h_{s1} - h_6) - \frac{w_p^*}{\eta_p} \tag{12.3}$$

where h_6 is the enthalpy of the primary liquid at conditions P_6 , T_6 as listed in suitable tables of properties.

The overall thermal efficiency of the cycle can now be calculated from the simple formula

$$\eta_c = \frac{w_{net}}{q_{in}} \tag{12.4}$$

Both η_c and w_{net} are useful parameters which characterize the overall thermodynamic performance of the EHD system.

Eq. (12.2) shows clearly how the ejector serves as a kind of amplifier which increases the electrical work output per unit mass of primary fluid. This effect is shown by the presence of the parameter x in the denominator of the first term. Notice the beneficial effect of a low value of x on parameters w_{net} and η_c . Unfortunately, the value of x cannot be stipulated independently in advance; it is fixed by the other specified input parameters as explained in the previous section.

Notice that owing to the fact that w_e^* is normally very small, it is possible in some circumstances for w_{net}

to take on values which are actually negative. When this happens it means that electrical power output is insufficient to drive the pump.

The relationships developed in this and the preceding sections make it possible to carry out systematic parametric studies of various one-fluid and two-fluid EHD cycles, with realistic allowances for the various losses that occur. Such studies can establish optimum design parameters and performance limits under various circumstances. These results in turn can finally permit informed conclusions to be drawn concerning the ultimate feasbility of this general type of EHD power generator.

13. Calculation Sequence

In this section we summarize the various equations previously derived in the approximate order in which they would be used in the calculation of system performance. Also listed are the initial input parameters whose values must be specified in order to start the calculation and various further input parameters whose values must be specified in order to proceed with various successive stages of the calculation.

Initial Input Data: $P_1 = P_2 = P_6$, T_1 , P_{s1} , T_{s1} , $(h_{s1} - h_1)$,
$\bar{R} = 8315$ Joule/kg°K

$$\gamma_1 = \left(1 - \frac{\ln(T_{s1}/T_1)}{\ln(P_{s1}/P_1)}\right)^{-1} \tag{13.1}$$

$$C_{p1} = \frac{(h_{s1} - h_1)}{(T_{s1} - T_1)} \tag{13.2}$$

$$R_1 = \left(\frac{\gamma_1 - 1}{\gamma_1}\right) C_{p1} \tag{13.3}$$

$$W_1 = \frac{\bar{R}}{R_1} \tag{13.4}$$

Further Input Data: W_v , $W_G = W_2$, $T_2 = T_6$, $P_v(T_6)$

$$\omega = \frac{W_v}{W_G} \frac{P_v(T_6)}{[P_2 - P_v(T_6)]} \tag{13.5}$$

Verify that $\omega << 1$

Further Input Data: γ_2 , $\left(\frac{V_1}{V_2}\right) = y$

$$M_1 = \sqrt{\frac{2}{(\gamma_1 - 1)}\left[\left(\frac{T_{s1}}{T_1}\right) - 1\right]} \tag{13.6}$$

$$M_2 = \left(\frac{V_2}{V_1}\right)\sqrt{\frac{\gamma_1 \; R_1 \; T_{s1}}{\gamma_2 \; R_2 \; T_2}} \quad \frac{M_1}{\sqrt{T_{s1}/T_1}} \tag{13.7}$$

Verify that $M_2 < 1$ (13.8)

$$\left(\frac{T_{s2}}{T_2}\right) = 1 + \left(\frac{\gamma_2 - 1}{2}\right) M_2{}^2 \tag{13.9}$$

$$T_{s2} = T_2 (T_{s2}/T_2) \tag{13.10}$$

$$\left(\frac{P_{s2}}{P_2}\right) = \left(\frac{T_{s2}}{T_2}\right)^{\frac{\gamma_2}{(\gamma_2 - 1)}} \tag{13.11}$$

$$P_{s2} = P_2 \left(\frac{P_{s2}}{P_2}\right) \tag{13.12}$$

Further Input Data: x (trial value)

$$R_2 = \frac{\overline{R}}{W_2} \tag{13.13}$$

$$R_3 = xR_1 + (1 - x)\; R_2 \tag{13.14}$$

$$C_{p2} = \frac{\gamma_2 \; R_2}{(\gamma_2 - 1)} \tag{13.15}$$

$$C_{p3} = x \; C_{p1} + (1 - x) \; C_{p2} \tag{13.16}$$

$$\gamma_3 = \frac{C_{p3}}{(C_{p3} - R_3)} \qquad (13.17)$$

$$T_{s3} = \frac{1}{C_{p3}} [x \; C_{p1} \; T_{s1} + (1 - x) \; C_{p2} \; T_{s2}] \qquad (13.18)$$

$$f(M_1) = M_1 \left[1 + \frac{\gamma_1 - 1}{2} \; M_1{}^2 \right]^{-\frac{(\gamma_1 + 1)}{2(\gamma_1 - 1)}} \qquad (13.19)$$

$$f(M_2) = M_2 \left[1 + \frac{\gamma_2 - 1}{2} \; M_2{}^2 \right]^{-\frac{(\gamma_2 + 1)}{2(\gamma_2 - 1)}} \qquad (13.20)$$

$$\frac{A_1}{A_2} = \frac{x}{(1 - x)} \left(\frac{P_{s2}}{P_{s1}} \right) \sqrt{\frac{R_1 \; T_{s1} \; \gamma_2}{R_2 \; T_{s2} \; \gamma_1} \; \frac{f(M_2)}{f(M_1)}} \qquad (13.21)$$

$$\frac{A_1}{A_3} = \frac{(A_1/A_2)}{(1 + A_1/A_2)} \qquad (13.22)$$

<u>Further Input Data:</u> P_o , T_o

$$s_1 = C_{p1} \; \ln \left(\frac{T_{s1}}{T_o} \right) - R_1 \; \ln \left(\frac{P_{s1}}{P_o} \right) \qquad (13.23)$$

$$s_2 = C_{p2} \; \ln \left(\frac{T_{s2}}{T_o} \right) - R_2 \; \ln \left(\frac{P_{s2}}{P_o} \right) \qquad (13.24)$$

$$\ln \left(\frac{P_{sx}}{P_o} \right) = \frac{1}{R_3} \left\{ C_{p3} \; \ln \left(\frac{T_{s3}}{T_o} \right) - x \; s_1 - (1 - x) \; s_2 \right\} \qquad (13.25)$$

$$P_{sx} = P_o \; e^{\ln (P_{sx}/P_o)} \qquad (13.26)$$

$$f(M_x) = f \frac{(1 - A_1/A_3)}{(1 - x)} \left(\frac{P_{s2}}{P_{sx}}\right) \sqrt{\frac{R_3 \; T_{s3} \; \gamma_2}{R_2 \; T_{s2} \; \gamma_3}} \; f(M_2) \qquad (13.27)$$

$$f_{max} = \left(\frac{2}{\gamma_3 + 1}\right)^{\frac{(\gamma_3 + 1)}{2(\gamma_3 - 1)}} \qquad (13.28)$$

Verify that $f(M_x) = f < f_{max}$ (13.29)

For first approximation set $M_x = M_2$ (13.30)

Iterate using Eqs. (13.31), (13.32), (13.33).

$$F(M_n) = f\left(1 + \frac{(\gamma_3 - 1)}{2} \; M_n^{\,2}\right)^{\frac{(\gamma_3 + 1)}{2(\gamma_3 - 1)}} - M_n \qquad (13.31)$$

$$F'(M_n) = f \; \frac{(\gamma_3 + 1)}{2} \; M_n \left(1 + \frac{(\gamma_3 - 1)}{2} \; M_n^{\,2}\right)^{\frac{(3 - \gamma_3)}{2(\gamma_3 - 1)}} \qquad (13.32)$$

$$M_{(n + 1)} = M_n - \frac{F(M_n)}{F'(M_n)} \qquad (13.33)$$

Iteration converges to fix M_x

$$g(M_1) = \frac{M_1}{(1 + \gamma_1 \; M_1^{\,2})} \sqrt{1 + \left(\frac{\gamma_1 - 1}{2}\right) M_1^{\,2}} \qquad (13.34)$$

$$g(M_2) = \frac{M_2}{(1 + \gamma_2 \; M_2^{\,2})} \sqrt{1 + \left(\frac{\gamma_2 - 1}{2}\right) M_2^{\,2}} \qquad (13.35)$$

$$g(M_y) = g = \sqrt{\frac{R_3\ T_{s3}}{\gamma_3}} \left(\frac{x}{g(M_1)} \sqrt{\frac{R_1\ T_{s1}}{\gamma_1}} + \frac{(1 - x)}{g(M_2)} \sqrt{\frac{R\ T_{s2}}{\gamma_2}} \right)^{-1} \qquad (13.36)$$

$$M_y^{\ 2} = \frac{(1 - 2\gamma_3\ g^2) - \sqrt{1 - 2\ (\gamma_3 + 1)\ g^2}}{1 - \gamma_3\ (1 - 2\gamma_3\ g^2)} \qquad (13.37)$$

Eq. (13.37) applies provided that $g \neq g_\infty = \frac{1}{\gamma_3} \sqrt{\frac{(\gamma_3 - 1)}{2}}$ (13.38)

If $g = g_\infty$ the solution reduces to

$$M_y = \sqrt{\frac{(\gamma_3 - 1)}{2\gamma_3}} \qquad (13.39)$$

Once M_y is known from Eq. (13.37) or (13.39)

$$f(M_y) = M_y \left(1 + \frac{(\gamma_3 - 1)}{2}\ M_y^{\ 2}\right)^{-\frac{(\gamma_3 + 1)}{2(\gamma_3 - 1)}} \qquad (13.40)$$

$$P_{sy} = P_{sx} \frac{f(M_x)}{f(M_y)} \qquad (13.41)$$

Further Input Data: η_E

$$P_{s3} = P_{sx} \left(\frac{P_{sy}}{P_{sx}}\right)^{1/\eta_E} \qquad (13.42)$$

$$f(M_3) = \left(\frac{P_{sx}}{P_{s3}}\right)\ f(M_x) \qquad (13.43)$$

Verify that $f(M_3) = f < f_{Max}$ (13.44)

For a first approximation take $M_3 = M_Y$ (13.45)

Iterate using Eqs. (13.31); (13.32), (13.33).

Iteration converges to fix M_3 .

$$\left(\frac{T_{s3}}{T_3}\right) = \left[1 + \frac{(\gamma_3 - 1)}{2} M_3^2\right] \qquad (13.46)$$

$$T_3 = T_{s3}/(T_{s3}/T_3) \qquad (13.47)$$

$$\left(\frac{P_{s3}}{P_3}\right) = \left(\frac{T_{s3}}{T_3}\right)^{\frac{\gamma_3}{(\gamma_3 - 1)}} \qquad (13.48)$$

$$P_3 = P_{s3}/(P_{s3}/P_3) \qquad (13.49)$$

Further Input Data: η_D , $\left(\frac{A_3}{A_4}\right)$

$$P_{s4} = P_{s3}\, e^{-\left(1 - \eta_D\right)\left(\frac{\gamma_3 M_3^2}{2}\right)} \qquad (13.50)$$

$$f(M_4) = f = \left(\frac{P_{s3}}{P_{s4}}\right)\left(\frac{A_3}{A_4}\right) f(M_3) \qquad (13.51)$$

Verify that $f(M_4) = f<f_{max}$ (13.52)

For a first approximation take $M_4 = \left(\frac{A_3}{A_4}\right) M_3$ (13.53)

Iterate using Eqs. (13.31), (13.32), (13.33).

Iteration converges to fix M_4 .

$$T_{s4} = T_{s3} \qquad (13.54)$$

$$\frac{T_{s4}}{T_4} = 1 + \frac{(\gamma_3 - 1)}{2} M_4^{\,2} \qquad (13.55)$$

$$T_4 = T_{s4}/(T_{s4}/T_4) \qquad (13.56)$$

$$\frac{P_{s4}}{P_4} = \frac{T_{s4}}{T_4}^{\frac{\gamma_3}{(\gamma_3 - 1)}} \qquad (13.57)$$

$$P_4 = P_{s4}/(P_{s4}/P_4) \qquad (13.58)$$

<u>Further Input Data</u>: $\varepsilon = 8.854 \times 10^{-12}$ farad/m, C_{B1} , C_{B2},
($C_B = 9.5 \times 10^3\ m^2$ °K/cmb for air or steam)

$$C_{B3} = \frac{1}{R_3} [x\ R_1\ C_{B1} + (1 - x)\ R_2\ C_{B2}] \qquad (13.59)$$

$$\beta = \frac{\varepsilon\ C_{B3}^{\,2}\ P_o}{T_o^{\,2}} \qquad (13.60)$$

$$\frac{\Delta T_s}{T_{s4}} = \beta \left(\frac{\gamma_3 - 1}{2\gamma_3}\right)\left(\frac{P_{s4}}{P_o}\right)\left(\frac{T_o}{T_{s4}}\right)^2 \left(1 + (\frac{\gamma_3 - 1}{2}) M_4^{\,2}\right)^{-1/(\gamma_3 - 1)} \qquad (13.61)$$

$$\frac{T_{s5}}{T_{s4}} = (1 - \frac{\Delta T_s}{T_{s4}}) \qquad (13.62)$$

$$P_{s5} = P_{s4}\ (\frac{T_{s5}}{T_{s4}})^{\gamma_3/(\gamma_3 - 1)} \qquad (13.63)$$

$$f(M_5) = f = \sqrt{\frac{T_{s5}}{T_{s4}}}\left(\frac{P_{s4}}{P_{s5}}\right) f(M_4) \tag{13.64}$$

Verify that $f(M_5) = f < f_{max}$ (13.65)

For a first approximation take $M_5 = M_4$ (13.66)

Iterate using Eqs. (13.31), (13.32), (13.33)

Iteration converges to fix M_5 .

$$\left(\frac{T_{s5}}{T_5}\right) = 1 + \left(\frac{\gamma_3 - 1}{2}\right) M_5{}^2 \tag{13.67}$$

$$T_5 = T_{s5}/(T_{s5}/T_5) \tag{13.68}$$

$$\left(\frac{P_{s5}}{P_5}\right) = \left(\frac{T_{s5}}{T_5}\right)^{\frac{\gamma_3}{(\gamma_3 - 1)}} \tag{13.69}$$

$$P_5 = P_{s5}/(P_{s5}/P_5) \tag{13.70}$$

Further Input Data: c_f

$$E(x) = (1 - \frac{p_z}{p_5}) + (1 - x - \frac{c_f}{2})\gamma_3 M_5{}^2 \tag{13.71}$$

$$- (1 - x)\gamma_3 M_5 M_z \sqrt{\frac{\gamma_2}{\gamma_3} \cdot \frac{R_2}{R_3} \cdot \frac{T_z}{T_5}} = 0$$

Iterate from Eq. (13.14) until x converges.

Further Input Data: (P_{s1}/P_{s7}), ρ_6, $(h_{s1} - h_6)$, η_x, η_p

$$P_{s7} = P_{s1}/(P_{s1}/P_{s7}) \qquad (13.72)$$

$$w_e^* = C_{p3}\,\Delta T_s \qquad (13.73)$$

$$w_p^* = \frac{(P_{s7} - P_6)}{\rho_6} \qquad (13.74)$$

$$w_{net} = \left(\frac{\eta_x\, w_e^*}{x} - \frac{w_p^*}{\eta_p}\right) \qquad \underline{\underline{\text{RESULT}}} \qquad (13.75)$$

$$q_{in} = (h_{s1} - h_6) - \frac{w_p^*}{\eta_p} \qquad (13.76)$$

$$\eta_c = \frac{w_{net}}{q_{in}} \qquad \underline{\underline{\text{RESULT}}} \qquad (13.77)$$

14. OPTIMUM VELOCITY RATIO

The calculation sequence summarized in the preceding section reveals that a comple cycle calculation requires us to specify numerical values for about thirty input parameters. One of these is the velocity ratio $(V_1/V_2) = y$. The calculation procedure outlined above then permits us to find the corresponding value of the mass flow ratio x , assuming that there exists a value of x which satisfies the governing thermodynamic relations for the specified values of the other input parameters.

If we now change the value of y but hold all other input parameters fixed, we can repeat the above procedure and find a corresponding new value of x , if such a value exists. It is evident, therefore, that x becomes some definite function of y as long as we remain in the domain where a real solution exists. Of course all other dependent variables of the cycle are also functions of y . In particular, the overall cycle efficiency η_c is some definite function of y . Moreover, for prescribed values of the other input parameters, there will be some definite value of y , let us designate it as the optimum value y_{opt} , which yields the greatest value of η_c that is possible under the specified input conditions. Our basic purpose therefore is to determine for any prescribed values of the other input parameters, the value of y_{opt} and the corresponding value of $\eta_c)_{max}$. Of course the values of x_{opt} and other dependent variables are also of interest.

Since a working computer program is now available to establish values of y_{opt}, $\eta_c)_{max}$, x_{opt} and so on for prescribed values of the other input parameters, we can proceed to study the effects of changes in these other parameters and to search systematically for such values of the most important input parameters as will yield the best overall performance of the system.

15. Conclusions and Recommendations

Based on the work reported here and in Ref. (6), the following conclusions are evident:

1) Ejector performance is substantially improved through the use of a high molecular weight primary fluid (i.e., above 100) and a low molecular weight secondary (i.e., below 30). The mixing penalty which ensues is offset by the substantial decrease in ejector losses.
2) The breakdown strength limitation is severe even at higher pressures. Since the breakdown strength of a mixture can often be smaller than that of a single fluid, allowance for this must be made when considering fluids to be used in the ejector. In Ref. (6) it is stated that in mercury/hydrogen an improvement by a factor of 5 in the breakdown strength is required for a competitive thermodynamic efficiency.
3) Consideration of the breakdown strength of mixtures together with other factors seem to indicate that the sequence of components shown in Fig. 1.1 might not be the best possible. In particular, serious thought should be given to an arrangement where the electrical section precedes the ejector. Here, mostly secondary fluid is present and the breakdown strength will be at its highest value.

The termination of the contract with DoE has left some questions about the two-fluid cycle unanswered. With the analysis presented in this report it should be possible to carry out further thermodynamic studies with various fluid combinations. Also, more fundamental knowledge on the breakdown strength of dielectric fluids will be necessary before the prospects for successful EHD power generation can be fully evaluated.

16. Sample Output

A sample output is shown in the following pages. The case is for mercury/hydrogen expanding from 1500 psia to 700 psia. The value of the breakdown constant, C_B, is 8000. The component loss parameters have numerical values corresponding to CASE B in Ref. 6.

```
FLUID PROPERTIES

 1  PS1= 1500.0   PSIA                  2  TS1= 1945.0   DEG R
 3  P1=   700.0   PSIA                  4  T1= 1730.0   DEG R
 5  (HS1-H1)=   13.50   BTU/LB          6  (HS1-H6)= 130.70   BTU/LB
 7  RHO6=  0.7500E 03   LB/FT3          8  CR1=   0.8000E 04   M2 DEG K/CMR

 9  NFLUID= 2                          10  WG=   0.2016E 01
11  GAMMA2= 1.4000                     12  CR2=   0.8000E 04   M2 DEG K/CMR

SYSTEM PARAMETERS

 1  ETAE= 0.85     2  ETAD= 0.85     3  A3/A4=0.250    4  CF= 0.80
 5  ETAX= 0.98     6  ETAP= 0.85     7  PS1/PS7= 1.00

COMPUTATIONAL FORMAT

 1  DELY= 0.10     2  YMIN= 1.00     3  YMAX= 5.00

 WV=  0.2058E 03(EFF MOL WT VAPOR)  GAMMA1= 1.1816  Y2CR= 0.1064

ENTER CONTROL CODE
>-4

       Y         X       A1/A3    OVERALL   RELATIVE       M3        M5
                                     EFF        EFF

    5.00    0.4375    0.0015    0.0228    0.2285    0.0285    0.0071

    4.90    0.4531    0.0017    0.0213    0.2135    0.0295    0.0074

    4.80    0.4375    0.0016    0.0228    0.2285    0.0296    0.0074

    4.70    0.4375    0.0016    0.0228    0.2285    0.0303    0.0076

    4.60    0.4277    0.0016    0.0238    0.2384    0.0307    0.0077

    4.50    0.4063    0.0015    0.0261    0.2620    0.0308    0.0077

    4.40    0.4219    0.0016    0.0244    0.2446    0.0319    0.0080

    4.30    0.4063    0.0016    0.0261    0.2620    0.0322    0.0080

    4.20    0.4063    0.0016    0.0261    0.2620    0.0329    0.0082

    4.10    0.3906    0.0015    0.0280    0.2807    0.0333    0.0083

    4.00    0.3906    0.0016    0.0280    0.2808    0.0341    0.0085

    3.90    0.3750    0.0015    0.0300    0.3011    0.0346    0.0086

    3.80    0.3594    0.0014    0.0322    0.3232    0.0350    0.0088

    3.70    0.3672    0.0015    0.0311    0.3119    0.0362    0.0091

    3.60    0.3594    0.0015    0.0322    0.3232    0.0370    0.0092

    3.50    0.3438    0.0015    0.0346    0.3473    0.0376    0.0094

    3.40    0.3477    0.0015    0.0340    0.3411    0.0388    0.0097

    3.30    0.3398    0.0015    0.0352    0.3537    0.0397    0.0099

    3.20    0.3281    0.0015    0.0372    0.3737    0.0406    0.0102

    3.10    0.3281    0.0015    0.0372    0.3737    0.0419    0.0105

    3.00    0.3125    0.0015    0.0401    0.4028    0.0428    0.0107
```

3.00	0.3125	0.0015	0.0401	0.4028	0.0428	0.0107
2.90	0.3125	0.0015	0.0401	0.4028	0.0443	0.0111
2.80	0.3125	0.0016	0.0401	0.4028	0.0458	0.0115
2.70	0.2969	0.0015	0.0433	0.4349	0.0470	0.0118
2.60	0.2969	0.0016	0.0433	0.4350	0.0488	0.0122
2.50	0.2969	0.0017	0.0433	0.4350	0.0508	0.0127
2.40	0.2891	0.0017	0.0451	0.4524	0.0526	0.0131
2.30	0.2813	0.0017	0.0469	0.4708	0.0546	0.0136
2.20	0.2813	0.0017	0.0469	0.4708	0.0570	0.0142
2.10	0.2734	0.0018	0.0488	0.4902	0.0594	0.0148
2.00	0.2734	0.0018	0.0488	0.4903	0.0624	0.0156
1.90	0.2656	0.0019	0.0509	0.5109	0.0653	0.0163
1.80	0.2656	0.0020	0.0509	0.5110	0.0689	0.0172
1.70	0.2656	0.0021	0.0509	0.5111	0.0730	0.0182
1.60	0.2656	0.0022	0.0509	0.5112	0.0775	0.0193
1.50	0.2656	0.0024	0.0509	0.5114	0.0827	0.0206
1.40	0.2734	0.0026	0.0489	0.4911	0.0890	0.0222
1.30	0.2813	0.0029	0.0470	0.4719	0.0964	0.0240
1.20	0.2969	0.0034	0.0435	0.4365	0.1056	0.0263
1.10	0.3125	0.0040	0.0403	0.4046	0.1165	0.0290

17. Computer Program

In the section the FORTRAN program used is listed. Results of our calculations are given in Ref. 6.

```
C TWO FLUID EHD GENERATOR
      IMPLICIT REAL*4 (A-H,O-Z)
      COMMON PS(6),TS(6),XM(6),P(6),T(6),RHO(6),S(6),V(4,7),
     + A1A3,A3A4,CP1,CP2,CP3,CB1,CB2,CB3,CF,DELH,DELH16,DELY,
     +DELTS,DELTS4,E,ETAE,ETAD,ETAX,ETAP,ETAC,FM1,FM2,FM3,FM4,FM5,FMX,
     +FMY,FMAX,FM3FMX,FM5FMX,GAMMA1,GAMMA2,GAMMA3,G11,G12,G13,G14,G15,
     +G16,G21,G22,G23,G24,G25,G26,G31,G32,G33,G34,G35,G36,G41,GM2,GMX,
     +XMX,XMY,XM0,XM1,NFLUID,PVT6,P0,PS1PS7,RIN,R1,R2,R3,
     +SMIX,T0,WC,WEX,WP,WNET,WO,WV,Y,YMIN,YMAX,TZ,XMZ,D1,FMZ,PZ,
     +U(10,12),W(2,3)
C DATA FILE
      U(1,1)=1500.
      U(1,2)=1079.3
      U(1,3)=900.
      U(1,4)=991.7
      U(1,5)=41.4
      U(1,6)=676.8
      U(1,7)=47.17
      U(1,8)=9490.
      U(1,9)=1.
      U(1,10)=18.
      U(1,11)=1.3
      U(1,12)=9490.
      U(2,1)=1500.
      U(2,2)=1089.4
      U(2,3)=800.
      U(2,4)=977.9
      U(2,5)=52.0
      U(2,6)=736.5
      U(2,7)=47.85
      U(2,8)=9490.
      U(2,9)=1.
      U(2,10)=13.
      U(2,11)=1.3
      U(2,12)=9490.
      U(3,1)=1500.
      U(3,2)=1109.2
      U(3,3)=700.
      U(3,4)=962.8
      U(3,5)=64.3
      U(3,6)=738.5
      U(3,7)=43.78
      U(3,8)=9490.
      U(3,9)=1.
      U(3,10)=13.
      U(3,11)=1.3
      U(3,12)=9490.
      U(4,1)=1500.
      U(4,2)=1115.6
      U(4,3)=600.
      U(4,4)=945.9
      U(4,5)=78.9
      U(4,6)=773.9
      U(4,7)=49.75
      U(4,8)=9490.
```

```
U( 4,9)=1.
U( 4,10)=18.
U( 4,11)=1.3
U( 4,12)=9490.
U( 5,1)=1500.
U( 5,2)=1133.5
U( 5,3)=500.
U( 5,4)=926.7
U( 5,5)=96.7
U( 5,6)=313.9
U( 5,7)=50.76
U( 5,8)=9490.
U( 5,9)=1.
U( 5,10)=18.
U( 5,11)=1.3
U( 5,12)=9490.
U( 6,1)=1500.
U( 6,2)=1945.
U( 6,3)=900.
U( 6,4)=1800.
U( 6,5)=8.
U( 6,6)=125.3
U( 6,7)=740.
U( 6,8)=4000.
U( 6,9)=2.
U( 6,10)=2.016
U( 6,11)=1.4
U( 6,12)=4000.
U( 7,1)=1500.
U( 7,2)=1945.
U( 7,3)=800.
U( 7,4)=1770.
U( 7,5)=11.
U( 7,6)=128.7
U( 7,7)=750.
U( 7,8)=4000.
U( 7,9)=2.
U( 7,10)=2.016
U( 7,11)=1.4
U( 7,12)=4000.
U( 8,1)=1500.
U( 8,2)=1945.
U( 8,3)=700.
U( 8,4)=1730.
U( 8,5)=13.5
U( 8,6)=130.7
U( 8,7)=750.
U( 8,8)=4000.
U( 8,9)=2.
U( 8,10)=2.016
U( 8,11)=1.4
U( 8,12)=4000.
U( 9,1)=1500.
U( 9,2)=2050.
U( 9,3)=600.
```

```
U(9,4)=1700.
U(9,5)=17.5
U(9,6)=135.3
U(9,7)=750.
U(9,8)=4000.
U(9,9)=2.
U(9,10)=2.015
U(9,11)=1.4
U(9,12)=4000.
U(10,1)=1500.
U(10,2)=2100.
U(10,3)=500.
U(10,4)=1600.
U(10,5)=19.5
U(10,6)=137.5
U(10,7)=750.
U(10,8)=4000.
U(10,9)=2.
U(10,10)=2.016
U(10,11)=1.4
U(10,12)=4000.
V(1,1)=1.
V(1,2)=1.
V(1,3)=0.
V(1,4)=0.
V(1,5)=1.
V(1,6)=1.
V(1,7)=1.
V(2,1)=.85
V(2,2)=.85
V(2,3)=.25
V(2,4)=.8
V(2,5)=.98
V(2,6)=.85
V(2,7)=1.
V(3,1)=.7
V(3,2)=.7
V(3,3)=1.
V(3,4)=2.
V(3,5)=.95
V(3,6)=.7
V(3,7)=1.
V(4,1)=.9
V(4,2)=1.
V(4,3)=1.
V(4,4)=0.
V(4,5)=1.
V(4,6)=.9
V(4,7)=1.
W(1,1)=.5
W(1,2)=1.
W(1,3)=2.
W(2,1)=.1
W(2,2)=1.
W(2,3)=5.
```

```
C   DATA INPUT
  500 WRITE(6,510)
  510 FORMAT('0',3X,'ENTER CONTROL CODE')
      READ(5,520) IU,IV,IW
  520 FORMAT(3I2)
      IF(IU.EQ.0)  STOP
      IF(IU.EQ.-2)  GO TO 130
      IF(IU.EQ.-3)  GO TO 300
      IF(IU.EQ.-4)  GO TO 232
  525 WRITE(6,530)
  530 FORMAT('0',3X,'ENTER FLUID PROPERTY CHANGES, IF ANY.')
      READ(5,540) JU,ZU
  540 FORMAT(I2,F9.4)
      IF(JU.EQ.0)  GO TO 550
      IF(JU.EQ.-1)  GO TO 500
      IF(JU.EQ.-2)  GO TO 130
      IF(JU.EQ.-3)  GO TO 300
      IF(JU.EQ.-4)  GO TO 232
      U(IU,JU)=ZU
      GO TO 525
  550 WRITE(6,560)
  560 FORMAT('0',3X,'ENTER SYSTEM PARAMETER CHANGES, IF ANY.')
      READ(5,540) JV,ZV
      IF(JV.EQ.0)  GO TO 570
      IF(JV.EQ.-1)  GO TO 500
      IF(JV.EQ.-2)  GO TO 130
      IF(JV.EQ.-3)  GO TO 300
      IF(JV.EQ.-4)  GO TO 232
      V(IV,JV)=ZV
      GO TO 550
  570 WRITE(6,580)
  580 FORMAT('0',3X,'ENTER FORMAT CHANGES, IF ANY.')
      READ(5,540) JW,ZW
      IF(JW.EQ.0)  GO TO 130
      IF(JW.EQ.-1)  GO TO 500
      IF(JW.EQ.-2)  GO TO 130
      IF(JW.EQ.-3)  GO TO 300
      IF(JW.EQ.-4)  GO TO 232
      W(IW,JW)=ZW
      GO TO 570
  130 PS(1)=U(IU,1)
      TS(1)=U(IU,2)
      P(1)=U(IU,3)
      T(1)=U(IU,4)
      DELH=U(IU,5)
      DELH16=U(IU,6)
      RHO(6)=U(IU,7)
      CB1=U(IU,8)
      GAMMA1=1.-ALOG(TS(1)/T(1))/ALOG(PS(1)/P(1))
      GAMMA1=1./GAMMA1
      G11=(GAMMA1-1.)/2.
      G12=G11+1.
      G13=GAMMA1/(GAMMA1-1.)
      G14=G13-1.
      G15=G12/(GAMMA1-1.)
```

```
      G16=G15-1.
      CP1=DELH/(TS(1)-T(1))
      R1=CP1/G13
      WV=1.98587/R1
      NFLUID=IFIX(U(IU,9))
      IF(NFLUID.EQ.1)   GO TO 400
      WG=U(IU,10)
      GAMMA2=U(IU,11)
      CB2=U(IU,12)
      GO TO 410
400   CB2=CB1
      GAMMA2=GAMMA1
      WG=WV
410   ETAE=V(IV,1)
      ETAD=V(IV,2)
      A3A4=V(IV,3)
      CF=V(IV,4)
      ETAX=V(IV,5)
      ETAP=V(IV,6)
      PS1PS7=V(IV,7)
      DELY=W(IW,1)
      YMIN=W(IW,2)
      YMAX=W(IW,3)
      P0=14.696
      T0=520.
      WRITE (6,140) PS(1),TS(1),P(1),T(1),DELH,DELH16,RHO(6),CB1,
     +NFLUID,WG,GAMMA2,CB2
140   FORMAT('0',3X,'FLUID PROPERTIES'//
     +4X,' 1  PS1=',F7.1,'  PSIA',13X,' 2  TS1=',F7.1,'  DEG R'/
     +4X,' 3  P1=',F7.1,'  PSIA',14X,' 4  T1=',F7.1,'  DEG R'/
     +4X,' 5  (HS1-H1)=',F7.2,'  BTU/LB',6X,' 6  (HS1-H6)=',F7.2,
     +'  BTU/LB'/
     +4X,' 7  RHO6=',E12.4,'  LB/FT3',5X,' 8  CB1=',E12.4,'  M2 DEG K/CM
     +B'//
     +4X,' 9  NFLUID=',I2,21X,'10  WG=',E12.4/
     +4X,'11  GAMMA2=',F7.4,16X,'12  CB2=',E12.4,'  M2 DEG K/CMB')
      WRITE(6,150) ETAE,ETAD,A3A4,CF,ETAX,ETAP,PS1PS7
150   FORMAT('0',3X,'SYSTEM PARAMETERS'//
     +4X,' 1  ETAE=',F5.2,3X,' 2  ETAD=',F5.2,3X
     +' 3  A3/A4=',F5.3,2X,' 4  CF=',F5.2/4X,' 5  ETAX=',F5.2,3X,
     +' 6  ETAP=',F5.2,5X,' 7  PS1/PS7=',F5.2)
      WRITE(6,155) DELY,YMIN,YMAX
155   FORMAT('0',3X,'COMPUTATIONAL FORMAT'//
     +4X,' 1  DELY=',F5.2,5X,' 2  YMIN=',F5.2,5X,' 3  YMAX=',F5.2)
160   Y=YMIN
      P(2)=P(1)
      P(6)=P(2)
      R2=1.98587/WG
      T(2)=T(1)
      T(6)=T(1)
      G21=(GAMMA2-1.)/2.
      G22= G21+1.
      G23= GAMMA2/(GAMMA2-1.)
      G24= G23-1.
      G25= G22/(GAMMA2-1.)
```

```
      G26=G25-1.
      XM(1)=(TS(1)/T(1)-1.)/G11
      XM(1)=SQRT(XM(1))
      Y2CR=XM(1)*SQRT(GAMMA1/GAMMA2*R1/R2*T(1)/T(2))
      FM1=XM(1)*(1.+G11*XM(1)**2)**(-G15)
      GM1=XM(1)/(1.+GAMMA1*XM(1)**2)*SQRT(1.+G11*XM(1)**2)
      WRITE (6,230) WV, GAMMA1,Y2CR
  230 FORMAT('0',4X,'WV=',E12.4,'(EFF MOL WT VAPOR)   GAMMA1=',F7.4,'
     +CR=',F7.4)
       GO TO 500
C   MOMENTUM FUNCTIONS
  800 Y=YMAX
  810 WRITE(6,820) Y
  820 FORMAT('0',4X,'Y=',F7.3)
      X=0.
  830 DO 850  LOOP=1,21
          XSMTM=EXCESS(X)
          WRITE(6,840)   X,XSMTM
  840     FORMAT(9X,'X=',F7.3,'   XSMTM=',E12.4)
          X=X+.05
  850     CONTINUE
      IF(Y.LE.YMIN)  GO TO 500
      Y=Y-DELY
      GO TO 810
C   EQUILIBRIUM AND PERFORMANCE
  232 WRITE(6,235)
  235 FORMAT('0',3X,'Y',9X,'X',5X,'A1/A3',3X,'OVERALL',
     +2X,'RELATIVE',3X,'M3',8X,'M5'/
     +37X,'EFF',7X,'EFF')
      Y=YMAX
  238 X=XZERO(Y)
  300 PS7=PS(1)/PS1PS7
      WE=CP3*DELTS
      WP=144./778.26*(PS7-P(6))/RHO(6)
      WEX=WE/X
      IF (WEX.LE.DELH)  GO TO 340
      WEX=DELH
      WRITE (6,320)
  320 FORMAT ('0',4X,'AVAILABLE ENTHALPY DROP ATTAINED')
  340 WNET=ETAX*WEX-WP/ETAP
      DIN=DELHIS-WP/ETAP
      ETAC=WNET/DIN
      WMAX=ETAX*DELH-WP/ETAP
      ETAR=WNET/WMAX
      WRITE (6,350) Y,X,A1A3,ETAC,ETAR,XM(3),XM(5)
  350 FORMAT('0',F9.2,6F10.4)
      Y=Y-DELY
      IF(Y.GE.YMIN)  GO TO 238
      GO TO  500
      END
C FUNCTION XMACH
      FUNCTION XMACH(FMN,G)
      IMPLICIT REAL*4(A-H,O-Z)
      MFLAG=0
      KOUNT=0
```

```
      G1=(G-1.)/2.
      G2=G1+1.
      G5=G2/(G-1.)
      G6=G5-1.
      XMN=0.
      FMAX=G2**(-G5)
      FMNFMX=FMN/FMAX
      IF(FMNFMX.LT.1.)  GO TO 1000
      XMACH=1.
      WRITE(6,1010) FMNFMX
 1010 FORMAT('0',3X,'FMN/FMAX=',F7.5,'  CHOKING LIMIT EXCEEDED')
      RETURN
 1000 F=FMN*(1.+G1*XMN**2)**G5-XMN
      IF(MFLAG.EQ.1)  WRITE(6,1030) XMN,F
 1030 FORMAT('0',3X,'M=',F7.5,'  F=',E12.4)
      DELF=ABS(F)
      IF(DELF.LT..5E-05)  GO TO 1020
      FP=FMN*G2*XMN*(1.+G1*XMN**2)**G6-1.
      XMN=XMN-F/FP
      KOUNT=KOUNT+1
      IF(KOUNT.LE.20)  GO TO 1000
      WRITE(6,1040) XMN,F
 1040 FORMAT('0',4X,'M=',F7.5,'  F=',E12.4,'  AFTER 20 ITERATIONS')
 1020 XMACH=XMN
      RETURN
      END
C FUNCTION XZERO(Y)
      FUNCTION XZERO(Y)
      IMPLICIT REAL*4 (A-H,O-Z)
      ITER=0
      XR=1.
      E=EXCESS(1.)
      ABSE=ABS(E)
      IF(ABSE.GE..5E-04)  GO TO 700
      XZERO=1.
      RETURN
  700 IF(E.GT.0.)  GO TO 720
      WRITE(6,710) E
  710 FORMAT('0',4X,'X=1.0  E=',E12.4.'  MOMENTUM DEFICIT')
      XZERO=1.
      RETURN
  720 XL=0.
      E=EXCESS(0.)
      ABSE=ABS(E)
      IF(ABSE.GE..5E-04)  GO TO 730
      XZERO=0.
      RETURN
  730 IF(E.LT.0.)  GO TO 750
      WRITE(6,740) E
  740 FORMAT('0',4X,'X=0.0  E=',E12.4,'  MOMENTUM INVERSION')
      XZERO=0.
      RETURN
  750 X=(XL+XR)/2.
      E=EXCESS(X)
      ABSE=ABS(E)
```

```
      ITER=ITER+1
      IF(ITER.LE.18)  GO TO 780
      WRITE(6,790)X,E
  790 FORMAT('0',4X,'X=',F7.5,'  E=',E12.4,'  AFTER 18 ITERATIONS')
      XZERO=X
      RETURN
  750 IF(ABSE.GE..5E-04)  GO TO 760
      XZERO=X
      RETURN
  760 IF(E.LT.0.)  GO TO 770
      XR=X
      GO TO 750
  770 XL=X
      GO TO 750
      END
C FUNCTION EXCESS(X)
      FUNCTION EXCESS(X)
      IMPLICIT REAL * 4 (A-H,O-Z)
      COMMON PS(6),TS(6),XM(6),P(6),T(6),RHO(6),S(6),V(4,7),
     + A1A3,A3A4,CP1,CP2,CP3,CB1,CB2,CB3,CF,DELH,DELH16,DELY,
     +DELTS,DELTS4,E,ETAE,ETAD,ETAK,ETAP,ETAC,FM1,FM2,FM3,FM4,FM5,FMX,
     +FMY,FMAX,FM3FMX,FM5FMX,GAMMA1,GAMMA2,GAMMA3,G11,G12,G13,G14,G15,
     +G16,G21,G22,G23,G24,G25,G26,G31,G32,G33,G34,G35,G36,GM1,GM2,GMX,
     +XMX,XMY,XK0,XK1,NFLUID,PVT6,P0,PSIPS7,QIN,R1,R2,R3,
     +SMIX,T0,WE,WEX,WP,WNET,WG,WV,Y,YMIN,YMAX,TZ,XMZ,D1,FMZ,PZ,
     +U(10,12),W(2,3)
      XM(2)= (XM(1)/Y)*SQRT((GAMMA1/GAMMA2)*(R1/R2)*(T(1)/T(2)))
      IF(XM(2).LT.1.)  GO TO 239
      XM(2)=1.
      T(2)=T(1)/Y**2*GAMMA1/GAMMA2*R1/R2
  239 TS2T2=1.+G21*XM(2)**2
      TS(2)= T(2)*TS2T2
      PS(2)= P(2)*TS2T2**G23
      GM2=XM(2)/(1.+GAMMA2*XM(2)**2)*SQRT(1.+G21*XM(2)**2)
  240 R3=X*R1+(1.-X)*R2
      CP2=G23*R2
      CP3=X*CP1+(1.-X)*CP2
      GAMMA3=CP3/(CP3-R3)
      G31=(GAMMA3-1.)/2.
      G32=G31+1.
      G33=GAMMA3/(GAMMA3-1.)
      G34=G33-1.
      G35=G32/(GAMMA3-1.)
      G36=G35-1.
      FMAX=G32**(-G35)
      TS(3)=(X*CP1*TS(1)+(1.-X)*CP2*TS(2))/CP3
      FM2=XM(2)*(1.+G21*XM(2)**2)**(-G25)
      D1=PS(2)/PS(1)*FM2/FM1*SQRT(R1/R2*TS(1)/TS(2)*GAMMA2/GAMMA1)
      A1A3=X*D1/(1.-X+X*D1)
      S(1)=CP1*ALOG(TS(1)/T0)-R1*ALOG(PS(1)/P0)
      S(2)=CP2*ALOG(TS(2)/T0)-R2*ALOG(PS(2)/P0)
      PSX=(CP3*ALOG(TS(3)/T0)-X*S(1)-(1.-X)*S(2))/R3
      PSX=P0*EXP(PSX)
      D2=PS(2)/PSX*FM2*SQRT(R3/R2*TS(3)/TS(2)*GAMMA2/GAMMA3)
      FMX=D2/(1.-X+X*D1)
```

```
      IF(FMX.LE.FMAX)   GO TO 241
      XMX=1.
      FMXFMX=FMX/FMAX
      FMX=FMAX
      WRITE (6,243) Y,X,FMXFMX
 243  FORMAT('0',4X,'Y=',F7.5,'   X=',F7.5,'   FMX/FMAX=',E12.4)
      GO TO 244
 241  XMX=XMACH(FMX,GAMMA3)
 244  GMY=SQRT(R3*TS(3)/GAMMA3)/(X/GM1*SQRT(R1*TS(1)/GAMMA1)+(1.-X)/GM2*
     +SQRT(R2*TS(2)/GAMMA2))
      GMAX=1./SQRT(2.*(GAMMA3+1.))
      IF(GMY.LE.GMAX)   GO TO 245
      GMYGMX=GMY/GMAX
      WRITE (6,242) Y,X,GMYGMX
 242  FORMAT('0',4X,'Y=',F7.5,'   X=',F7.5,'   GMY/GMAX=',E12.4/
     +5X,'MOMENTUM LIMIT EXCEEDED.')
      XMY=1.
      FMY=FMAX
      GO TO 248
 245  XMY=((1.-2.*GAMMA3*GMY**2)-SQRT(1.-2.*(GAMMA3+1.)*GMY**2))/
     +(1.-GAMMA3*(1.-2.*GAMMA3*GMY**2))
      XMY=SQRT(XMY)
      FMY=XMY/(1.+G31*XMY**2)**G35
      IF(FMY.LE.FMAX)   GO TO 248
      XMY=1.
      FMYFMX=FMY/FMAX
      FMY=FMAX
      WRITE (6,246) Y,X,FMYFMX
 246  FORMAT('0',4X,'Y=',F7.5,'   X=',F7.5,'   FMY/FMX=',E12.4)
 248  PSY=PSX*FMX/FMY
      PS(3)=PSX*((PSY/PSX)**(1./ETAE))
      FM3=PSX/PS(3)*FMX
      IF(FM3.LE.FMAX)   GO TO 249
      XM(3)=1.
      WRITE(6,900) XM(1),XM(2),XMX,XMY,XM(3),FM1,FM2,FMX,FMY,FM3,
     +FMAX,GM1,GM2,GMY,GMAX,PS(1),PS(2),PSX,PSY,PS(3),TS(1),
     +TS(2),TS(3)
 900  FORMAT('0',6X,'M1,M2,MX,MY,M3='/5E12.4/
     +'0','FM1,FM2,FMX,FMY,FM3,FMAX='/5E12.4,E11.4/
     +'0','GM1,GM2,GMY,GMAX='/4E12.4/
     +'0','PS1,PS2,PSX,PSY,PS3='/5E12.4/
     +'0','TS1,TS2,TS3='/3E12.4)
      FM3FMX=FM3/FMAX
      FM3=FMAX
      WRITE (6,251) Y,X,FM3FMX
 251  FORMAT('0',4X,'Y=',F7.5,'   X=',F7.5,'   FM3/FMAX=',E12.4)
      GO TO 247
 249  XM(3)=XMACH(FM3,GAMMA3)
 247  TS3T3=1.+G31*XM(3)**2
      T(3)=TS(3)/TS3T3
      PS3P3=TS3T3**G33
      P(3)=PS(3)/PS3P3
      PS(4)=PS(3)*EXP(-(1.-ETAD)*GAMMA3/2.*XM(3)**2)
      FM4=PS(3)/PS(4)*A3A4*FM3
      IF(FM4.LE.FMAX)   GO TO 252
```

```
      XM(4)=1.
      FM4FMX=FM4/FMAX
      FM4=FMAX
      WRITE(6,253) Y,X,FM4FMX
253   FORMAT('0',4X,'Y=',F7.5,'   X=',F7.5,'   FM4/FMAX=',E12.4)
      GO TO 254
252   XM(4)=XMACH(FM4,GAMMA3)
254   TS(4)=TS(3)
      TS4T4=1.+G31*XM(4)**2
      T(4)=TS(4)/TS4T4
      PS4P4=TS4T4**G33
      P(4)=PS(4)/PS4P4
      C83=X*C81+(1.-X)*C82
      BETA=0.0009675*(P0/14.696)*(C83/9490.*520./T0)**2
      DELTS4=BETA*G31/GAMMA3*PS(4)/P0*(T0/TS(4))**2/(1.+G31*XM(4)**2)**
     +G34
      DELTS=TS(4)*DELTS4
      TS(5)=TS(4)-DELTS
      PS(5)=PS(4)*(TS(5)/TS(4))**G33
      FM5=TS(5)/TS(4)*PS(4)/PS(5)*FM4
      IF(FM5.LE.FMAX)  GO TO 250
      XM(5)=1.
      FM5FMX=FM5/FMAX
      FM5=FMAX
      WRITE (6,255) Y,X,FM5FMX
255   FORMAT('0',4X,'Y=',F7.5,'   X=',F7.5,'   FM5/FMAX=',E12.4)
      GO TO 260
250   XM(5)=XMACH (FM5,GAMMA3)
260   TS5T5=1.+G31*XM(5)**2
      T(5)=TS(5)/TS5T5
      PS5P5=TS5T5**G33
      P(5)=PS(5)/PS5P5
      FMZ=(1.-X)*A3A4*FM2/(1.-X+X*D1)
      XMZ=XMACH(FMZ,GAMMA2)
      TSZTZ=1.+G21*XMZ**2
      TZ=TS(2)/TSZTZ
      PZ=PS(2)/(TSZTZ**G23)
      EXCESS=1.-PZ/P(5)+(1.-X-CF/2.)*GAMMA3*XM(5)**2-(1.-X)*GAMMA3*
     +XM(5)*XMZ*SQRT(GAMMA2/GAMMA3*R2/R3*TZ/T(5))
      RETURN
      END
```

18. Nomenclature

A - area

a - speed of sound

C_B - characteristic breakdown constant (Eqn 10.3)

C_p - specific heat at constant pressure

c_f - friction loss coefficient - condenser

E_b - breakdown electric field strength

$E(x)$ - Eqn. 11.5

$F(M_n)$ - Eqn. 5.16

$f(M)$ - Eqn. 5.3

f_{max} - Eqn. 5.15

$g(M)$ - Eqn. 7.5

g - Eqn. 7.7

g_{max} - Eqn. 7.9

g_{∞} - Eqn. 7.10

h - enthalpy

I - irreversibility

M - Mach number

$\dot{m}$ - mass flow rate

P_e - gross electrical power

p - pressure

q_{in} - heat input

R - gas constant

$\bar{R}$ - universal gas constant

s - entropy

s_m - entropy of mixing

T - temperature

V - velocity

W - molecular weight

w_e^* - gross work out per unit mass

w_p^* - ideal pump work per unit mass

w_{net} - useful electrical output per unit mass

x - $\dot{m}_1/\dot{m}_3$

y - v_1/v_3

z - quality of vapor

β - Eqn. 10.7, dimensionless breakdown constant

γ - ratio of specific heats

$\Delta(\ )$ - change of

ε - permittivity of the medium

η_c - overall cycle efficiency

η_E - Eqn. 8.13, ejector effectiveness

η_D - Eqn. 9.6, diffuser effectiveness

η_p - pump efficiency

η_x - excitation efficiency

ρ - gas density

ψ - steady flow availability

ω - mass ratio of condensible primary to dry secondary

Subscripts

0 - ambient conditions

1 - primary, entrance to ejector (exit from boiler/superheater)

2 - secondary, entrance to ejector (exit from separator)

3 - mixture, exit from ejector entrance to diffuser

4 - mixture, exit from diffuser entrance to generator

5 - mixture, exit from generator entrance to condenser

6 - primary, exit from condenser entrance to pump

7 - primary, exit from pump entrance to boiler

f - saturated liquid

G - gas or secondary

g - saturated vapor

n - next value

s - stagnation

v - vapor

x - exit station of hypothetical minimum loss device

y - exit station of ideal ejector

z - exit station of condenser

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