

# XI. ENERGY CONVERSION RESEARCH\*

## A. Power Systems with Liquid Generators

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#### 1. EXPERIMENTAL RESULTS FOR CONDENSING EJECTOR M-1

A detailed experimental program has been conducted on condensing ejector mixing section M-1 with steam and water used as the working fluids. The tests were made on the condensing ejector test facility which has been described in Quarterly Progress Reports No. 78 (pages 149-159) and No. 79 (pages 149-151).

Mixing section M-1 was machined from brass; the important details are shown in Fig. XI-1. The total length of the convergent mixing section, constant-area mixing section, and diffuser is 23.37 inches. The convergent section has an inlet diameter of 1.352 inches and is tapered to a diameter of 0.626 inch at its exit. The angle of taper is  $2.26^\circ$ . The constant-area section is approximately 7 inches in length and has an

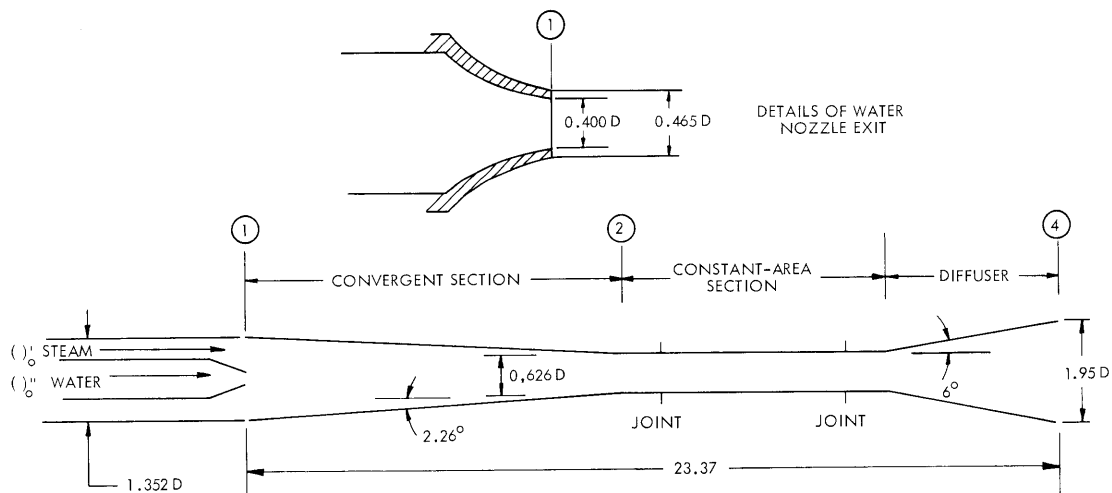


Fig. 1. Details of mixing section M-1.

\* This work is supported by the U. S. Air Force (Research and Technology Division) under Contract AF33(615)-3489 with the Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio.

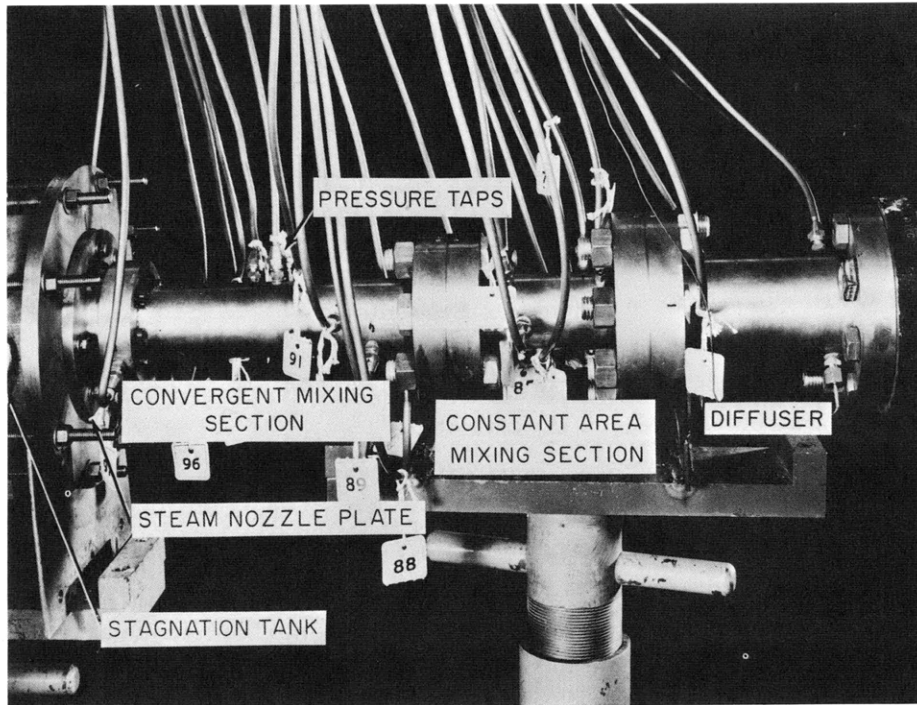


Fig. XI-2. Mixing section M-1 installation.

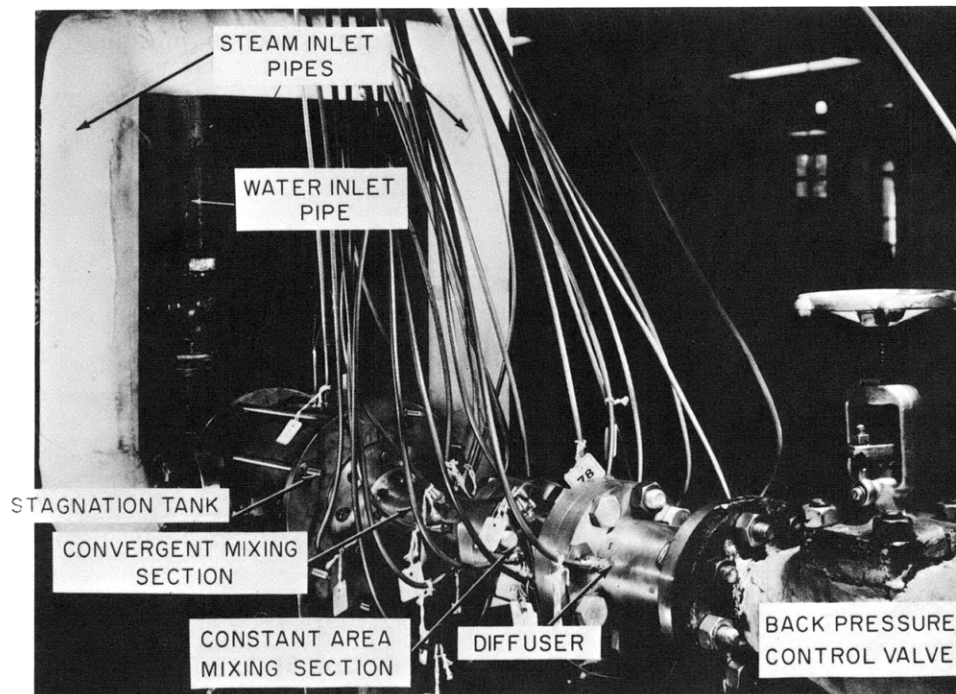


Fig. XI-3. Over-all view of mixing section M-1 installation.

inside diameter of 0.626 inch. The diffuser has a 6° angle of divergence with inlet and exit diameters of 0.626 and 1.95 inches, respectively. The water nozzle at the inlet of the convergent section has an inside diameter of 0.400 inch. The outside diameter is approximately 0.465 inch. The contours of the convergent section and diffuser are blended smoothly to the contour of the constant-area section. Pressure taps are located at numerous points along the condensing ejector.

The ratio of water-flow area to steam-flow area at section 1 ( $A_1''/A_1'$ ) is 0.1. The contraction ratio for the mixing section ( $A_1/A_2$ ) is 5.

Figure XI-2 shows the installation of the mixing section in the condensing ejector test facility. Figure XI-3 shows additional details of the installation. Detailed pictures of the stagnation tanks were given in Quarterly Progress Report No. 78 (pages 150, 151).

Mixing section M-1 has been tested for inlet steam pressures at 20-50 psia and for water inlet pressures as shown in Fig. XI-4. The steam velocity at section 1 was approximately sonic velocity. The steam was saturated at the inlet to the condensing ejector while the water inlet temperature was approximately 40°F. For the test results

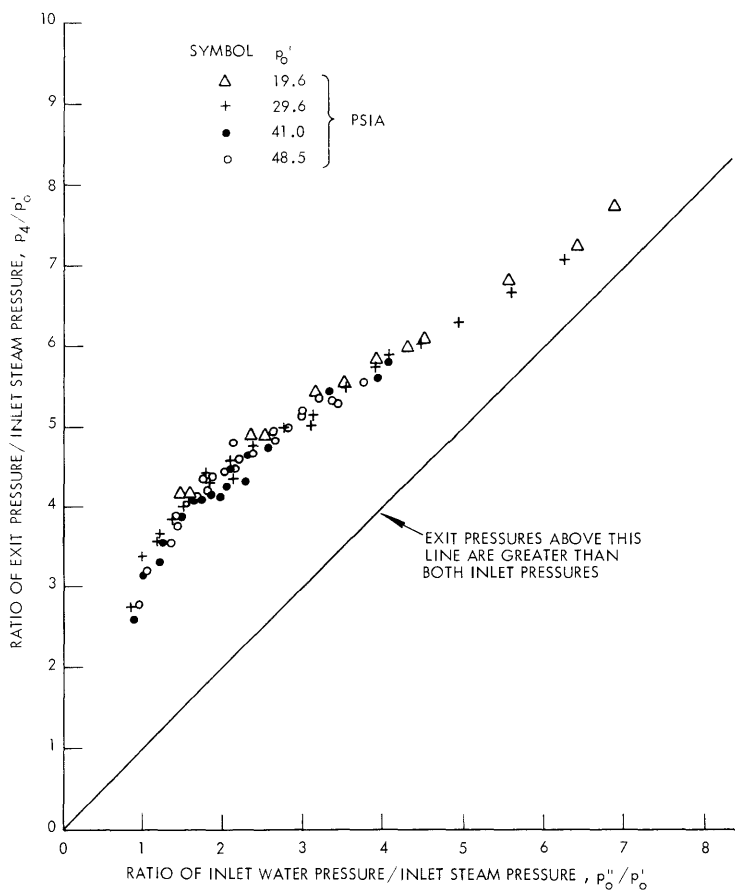


Fig. 4. Performance for mixing section M-1.

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in Fig. XI-4 the pressure discontinuity was moved as far upstream as possible in the constant-area section and the diffuser exit pressure ( $p_4$ ) was measured. This location of the discontinuity is such that any farther upstream movement would cause the discontinuity to move rapidly through the convergent section and change the conditions at section 1. For these test conditions no major effects of the inlet steam pressure ( $p'_0$ ) are observable. All test conditions correspond to exit pressures greater than the inlet pressures. The exit pressure varies linearly with the inlet water pressure above values of  $p''_0/p'_0 \approx 1.5$ . This behavior is expected theoretically. Theoretical values of the exit pressure, although not shown, are in good agreement with predicted values. For values of  $p''_0/p'_0$  less than 1.5, the exit pressures are lower than expected. In this range the details of the mixing process must be known. This information is being obtained with the new plastic sections.

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## B. Alkali-Metal Magnetohydrodynamic Generators

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### 1. PERFORMANCE POTENTIAL OF SUPERHEATED RANKINE CYCLE SPACE POWER SYSTEMS EMPLOYING MAGNETOHYDRODYNAMIC GENERATORS

The Rankine cycle space power system is generally considered to have a higher specific power potential than the Brayton cycle system, particularly in the megawatt range.

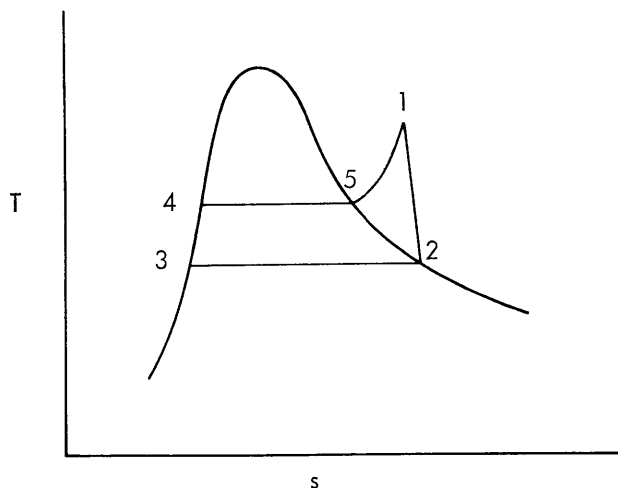


Fig. XI-5. Superheated Rankine cycle employing dry vapor in the MHD generator.

This conclusion is predicated on the assumption that even with the use of condensable metal vapors in the Rankine cycle, the maximum cycle temperature and component specific weights are not substantially different from those for the Brayton cycles.

When high-temperature reactors capable of surface temperatures over  $2000^{\circ}\text{K}$  are developed, the use of magnetohydrodynamic generators becomes attractive for large space power systems in the megawatt range. Even at these high surface temperatures, however, thermal ionization is inadequate for providing the necessary electrical

conductivity of the metal vapor, and nonequilibrium ionization must be employed.

It has been verified experimentally that dry potassium vapor can yield nonequilibrium electrical conductivities above 1 mho/cm at pressures of approximately .01 atm.<sup>1</sup> This

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is adequate for an efficient MHD generator. Thus alkali metals could be employed in a superheated Rankine cycle of the type shown in Fig. XI-5.

The optimum radiator temperature,  $T_2$ , for maximum specific power for this cycle, under the assumption of a fixed  $T_1$ , can be shown to be given implicitly by

$$\gamma_c \triangleq \frac{a\epsilon\sigma T_1^4}{b} = \left(\frac{T_1}{T_2}\right)_{\text{opt}}^5 \left[ 4 - 5\left(\frac{T_2}{T_1}\right)_{\text{opt}} \right],$$

where

$a$  = radiator specific area,  $A_r/m_r$  ( $m^2/kg$ )

$b$  = reactor heat source specific power,  $P_s/m_s$  ( $kw/kg$ )

$\epsilon$  = emissivity of the radiation

$\sigma$  = Stefan-Boltzmann constant

$T_1$  = maximum cycle temperature.

The corresponding optimum cycle efficiency is given by

$$\eta_{R(\text{opt})} = \frac{1}{H} \frac{\left[ 1 - \left(\frac{T_2}{T_1}\right)_{\text{opt}} \right]}{1 + \frac{1}{H} \left[ 1 - \left(\frac{T_2}{T_1}\right)_{\text{opt}} \right]},$$

where

$$H \triangleq \frac{\gamma - 1}{\gamma} \frac{h_{fg}}{RT_1}.$$

Here it is assumed that the vapor is a perfect gas and that the liquid phase has a constant heat of vaporization,  $h_{fg}$ .

The maximum specific power can be calculated from

$$a_{\text{max}} \triangleq \frac{P_e}{M_e} = b\eta_{R(\text{opt})} \frac{1}{\left[ 1 + \frac{(1-\eta_{R(\text{opt})})}{\gamma_c \left(\frac{T_2}{T_1}\right)_{\text{opt}}^4} \right]}.$$

For a radiator-dominated system,  $\gamma_c$  approaches zero and  $(T_2/T_1)_{\text{opt}} \Rightarrow 0.8$ . The

optimum cycle efficiency and maximum specific power have the simple approximate forms

$$\eta_{R(\text{dry})} \approx \left( \frac{0.2}{H} \right)$$

$$a_{\text{dry}} \approx 0.41 \left( a_{\epsilon\sigma} T_1^4 \right) \left( \frac{\eta_{R(\text{dry})}}{1 - \eta_{R(\text{dry})}} \right).$$

If we are able to operate the MHD generator into the wet region, as illustrated by the cycle in Fig. XI-6, substantial gains in specific power are possible.

An estimate of the gains to be made by operating into the wet regime can be obtained

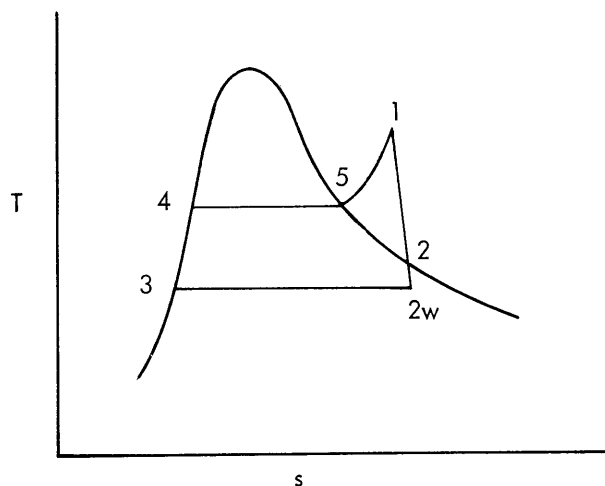


Fig. 6. Superheated Rankine cycle utilizing an MHD generator that operates into the wet region.

by assuming the same radiator temperature,  $T_{2W}$ , as for the dry cycle. For a radiator-dominated system with  $T_{2W}/T_1 = 0.8$  we obtain

$$\eta_{R(\text{wet})} \approx \eta_{R(\text{dry})} [1 + 5H\mu]$$

$$a_{(\text{wet})} \approx a_{(\text{dry})} \frac{\left( \frac{\eta_{R(\text{wet})}}{1 - \eta_{R(\text{wet})}} \right)}{\left( \frac{\eta_{R(\text{dry})}}{1 - \eta_{R(\text{dry})}} \right)}.$$

Consider lithium with  $H \approx 2.3$  for  $T_1 = 2000^\circ\text{K}$ . Then for 5 per cent moisture, the cycle efficiency and specific power are both increased more than 50 per cent over the dry-cycle values.

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It should be noted that the cycle just discussed requires the boiler temperature,  $T_5$ , to increase as  $\mu$  is increased. If the maximum permissible boiler temperature of the reactor is limited, a more conservative cycle for comparison purposes might be one in which  $T_1$ ,  $T_2$ , and  $T_5$  are all maintained at the same values as for the optimum dry-vapor Rankine cycle. The MHD generator would then be assumed to be made somewhat longer to allow operation into the wet regime of point 2W.

For this cycle the fractional wetness,  $\mu$ , is a function of both  $(T_{2W}/T_1)$  and the generator efficiency. For lithium, under the perfect gas assumptions, we obtain approximately 5 per cent moisture for  $T_{2W}/T_1 = 0.7$  and  $\eta_{gen} \approx 75$  per cent. This results in a cycle efficiency and specific power for a radiator-dominated system given by

$$\eta_{R(wet)} \approx 2\eta_{R(dry)}$$

$$a_{(wet)} \approx 1.25a_{(dry)}$$

Therefore, even for this very conservative case, the cycle efficiency is approximately double, and the specific power is increased about 25 per cent over the dry vapor values.

These potential increases in specific power to be obtained by operating into the wet region are predicated under the assumption that the generator efficiency remains near the dry-vapor value. If the generator efficiency decreases appreciably in the wet regime, King<sup>2</sup> has shown that the best specific power is obtained by operating only with dry vapor to the saturated vapor line as in Fig. XI-5.

A recent theoretical study by Solbes<sup>3</sup> indicates that under certain conditions with drop radius large compared with the Debye length, nonequilibrium ionization can be sustained in a wet vapor. His initial experimental results tend to support this conclusion.

If nonequilibrium ionization can be obtained and sustained in a wet vapor, high generator efficiency in the wet regime should be attainable. The substantial increases in specific power which would then be possible provide strong motivation for the present study of the electrical conductivity of wet potassium vapor.

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References

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2. R. King, "Performance Analyses of MHD Generators with Alkali Metal Working Fluids," S.M. Thesis, Massachusetts Institute of Technology, Cambridge, Mass., June 1965.
3. J. L. Kerrebrock, M. A. Hoffman, and A. Solbes, "Characteristics of a Pure Alkali-Metal Vapor Plasma," Quarterly Progress Report No. 79, Research Laboratory of Electronics, M.I.T., October 15, 1965, pp. 167-174.