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A 4-KILOWATT STEAM RANKINE CYCLE SOLAR POWER SYSTEM

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A recent study[1] of a Rankine cycle space power system concluded that steam compared favorably with mercury as a working fluid. That study concentrated primarily on a 30-kilowatt system using both solar and nuclear heat sources. The objective of the study reported herein was to investigate the merit of using steam in a smaller solar system comparable in power to the Sunflower I, a 3-kilowatt system. The intent was to find any large effects brought about by utilizing steam instead of mercury; therefore detailed component design study was not undertaken.

The Sunflower I solar collector and boiler - heat storage unit were utilized in the study as a starting point. Thus several of the Sunflower component weights were applicable here. The heat energy input at the boiler was kept at a constant 34.3 kilowatts thermal, as in the present Sunflower I system.[2]

The important assumptions used for this study are as follows:

(1) Expansion efficiencies, 0.5, 0.6, and 0.7

(2) Alternator efficiencies, 0.8 and 0.87

(3) Percent of alternator output available to payload, 0.85

(4) Peak cycle temperature and pressure, 1200° F and 1000 psia, respectively

(5) Recuperator effectiveness, 1.0

(6) Radiator:

  (a) Direct condensing fin and tube

  (b) Material, aluminum

  (c) Meteoroid flux,[3] Whipple's (1963)

  (d) Meteoroid density, 0.6 grams per cubic centimeter

  (e) Armor thickness calculation from reference 4

  (f) Equivalent sink temperature, 400° R

A schematic diagram of the system is shown in figure 1. The distinguishing feature of the steam system, compared with Sunflower I, is the recuperator, which is necessary to improve cycle efficiency and to reduce the heat load on the radiator. The temperature-entropy diagram (fig. 2) shows that the entire expansion, from point 1 to point 2, takes place in the superheat region. From this the necessity of the recuperator becomes apparent. After passing through the recuperator, from point 2 to point 3, the fluid emerges as saturated vapor. The fluid is condensed and subcooled to point 5; then after passing through the pump, the condensate is heated in the recuperator from point 6 to point 7 before reentering the boiler. The vapor and the condensate would not be mixed; therefore there would be no change of phase in the recuperator. For the prime mover, both a turbine and a reciprocating expander were considered but at this power level, use of a turbine did not appear attractive because the volume flow was very low. Thus the turbine was dropped from further consideration. The range of expander pressure ratios p_1/p_2 considered was from 5 to 30, for which the corresponding radiator inlet temperature varied from 381° to 256° F. Coincidentally, the boiling temperature of 550° to 600° F is the approximate heat rejection temperature of Sunflower I. A plot of thermodynamic cycle efficiency versus expander pressure ratio is shown in figure 3. Also shown in figure 3 is the alternator output using an alternator efficiency of 0.87. For an expander pressure ratio of 15 or higher, the thermodynamic cycle efficiency (eq. (1)) would be in excess of 15 percent:

$$\eta_{th} = \frac{\eta_{ex}(h_1 - h_{2,id}) - \dfrac{h_{6,id} - h_5}{\eta_P}}{(h_1 - h_6) - (h_2 - h_3)E} \tag{1}$$

where recuperator efficiency E (eq. (2)) was assumed to be unity:

$$E = \frac{h_7 - h_6}{h_2 - h_3} \tag{2}$$

and the expansion efficiency

$$\eta_{ex} = \frac{h_1 - h_2}{h_1 - h_{2,id}} \tag{3}$$

While thermodynamic cycle efficiency increased with increasing expander pressure ratio, so also did the specific radiator area increase as shown in figure 4. The increase was due primarily to the lower condensing temperature. The fin effectiveness used was 0.6. At any given expander pressure ratio, a significant change occurs in the specific radiator area with change in expansion efficiency, because of the change in alternator output. At an expander pressure ratio of 20, the specific radiator area was 70 square feet per electrical kilowatt for an expansion efficiency of 0.7 and 100 square feet per electrical kilowatt for an expansion efficiency of 0.5. The expansion efficiency had only a small effect on the actual radiator area, however, as can be seen in figure 5.

The expander pressure ratio affects the system specific weight as shown in the lower half of figure 5. In all cases, the system specific weight minimized at an expander pressure ratio of approximately 20. For an expansion efficiency in the 0.5 to 0.6 range, which apparently can be achieved,[5] the system specific weight was not too different from the Sunflower I reference system weight of 233 pounds per kilowatt. However, the radiator area, plotted above system weight in figure 5, would be approximately 450 square feet for the same expander pressure ratio. The Sunflower I radiator area is approximately 90 square feet or 30 square feet per kilowatt. The large radiator (70 sq ft/kw) of the steam system would probably be objectionable. Therefore the fin effectiveness was increased from 0.6 to 0.95 to determine what reduction of area would cost in increased weight. The fin effectiveness of 0.6 is approximately the value at which radiator weight minimized. For an expander pressure ratio of 20 and an expansion efficiency of 0.6, the radiator area for a fin effectiveness of 0.95 was 250 square feet or about 50 square feet per kilowatt and the system specific weight was increased by about 12 pounds per kilowatt.

A reciprocating expander operating at 3600 rpm and a pressure ratio of 20 would have a displacement of about 10 cubic inches. This low rotational speed, compared with 40,000 rpm for Sunflower I, would probably increase the size of the alternator. For this reason, a specific weight of 15 pounds per kilowatt generated was used.

A weight breakdown for an expander pressure ratio of 20 and an expansion efficiency of 0.6 is shown in figure 6. The fixed weights with two exceptions are the same as for Sunflower I. The recuperator weight and an additional 30 pounds for structure to take care of the additional radiator area were added. Including the radiator, reciprocating expander, and alternator weights, the total system weight was 950 pounds, 200 or 220 pounds per kilowatt depending upon the alternator efficiency used.

To summarize, the steam system appears to have no significant specific weight advantage over the Sunflower I mercury system. The slightly higher thermodynamic cycle efficiency would enable the steam system to produce more electric power than the mercury system using the same solar collector and heat storage unit. However, the larger radiator area must be listed as a definite liability to the steam system.

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SCHEMATIC OF STEAM RANKINE CYCLE UTILIZING SUNFLOWER I COLLECTOR

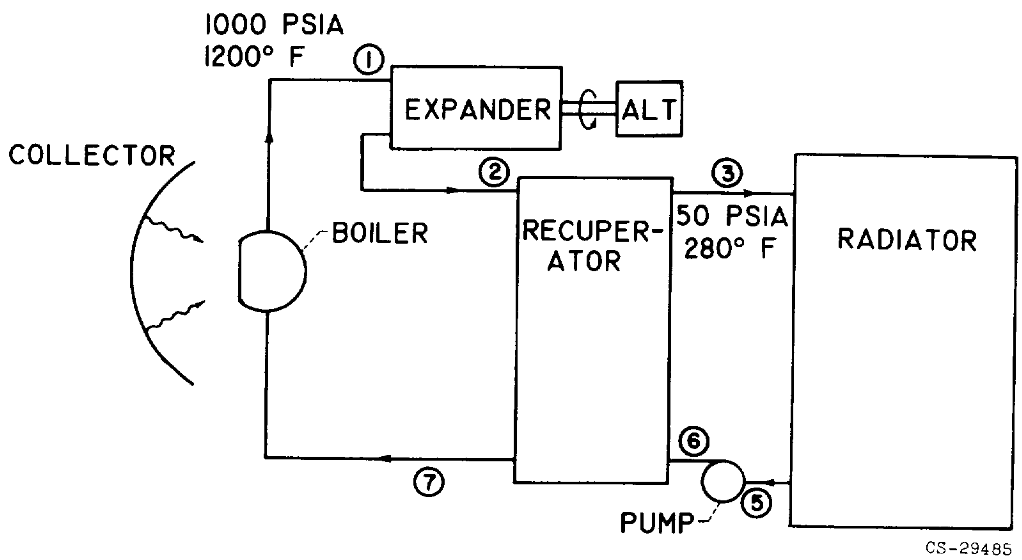

Fig. 1.

TEMPERATURE–ENTROPY DIAGRAM

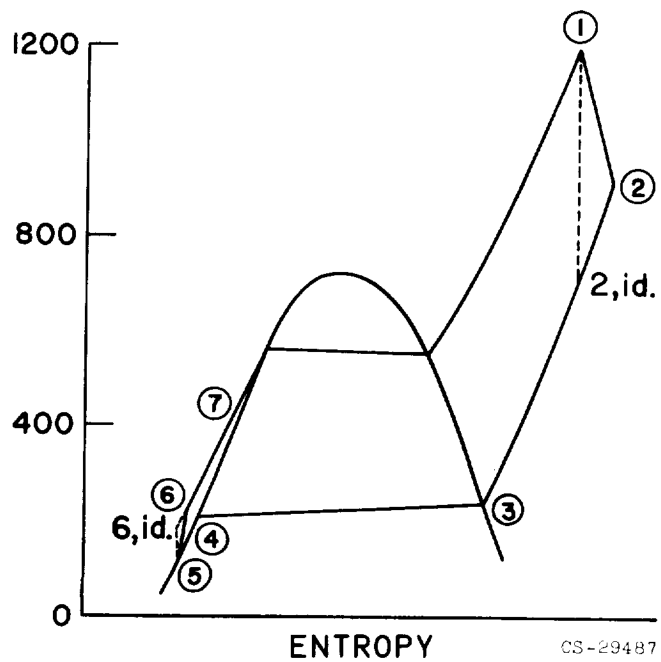

Fig. 2.

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EFFECT OF EXPANDER PRESSURE RATIO AND EFFICIENCY ON THERMODYNAMIC CYCLE EFFICIENCY

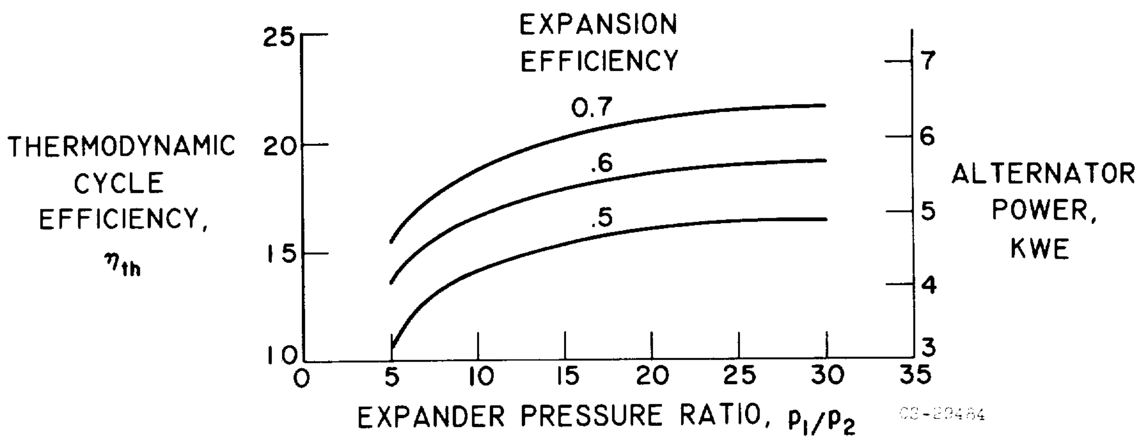

Fig. 3.

EFFECT OF EXPANDER PRESSURE RATIO AND EFFICIENCY ON SPECIFIC RADIATOR AREA

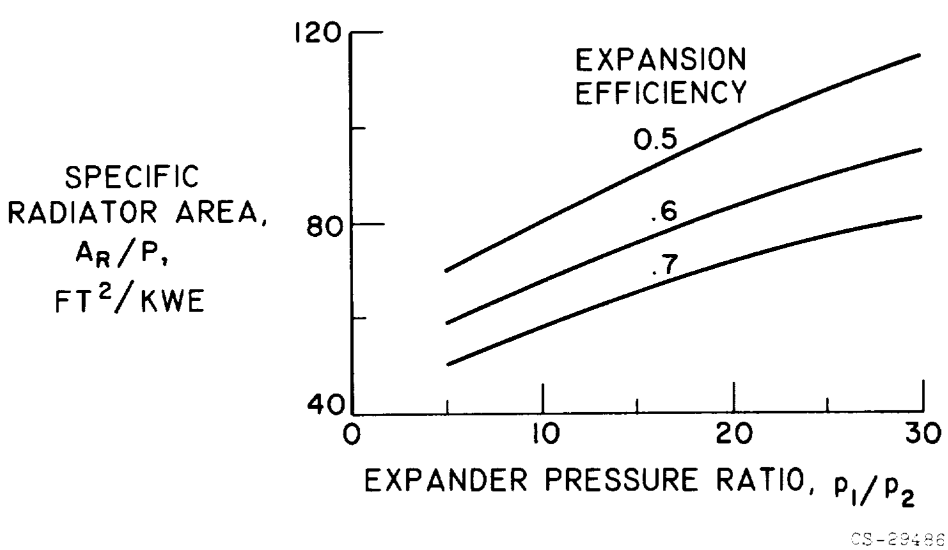

Fig. 4.

SYSTEM SPECIFIC WGT. AND RADIATOR AREA AS A FUNCTION OF EXPANDER PRESSURE RATIO

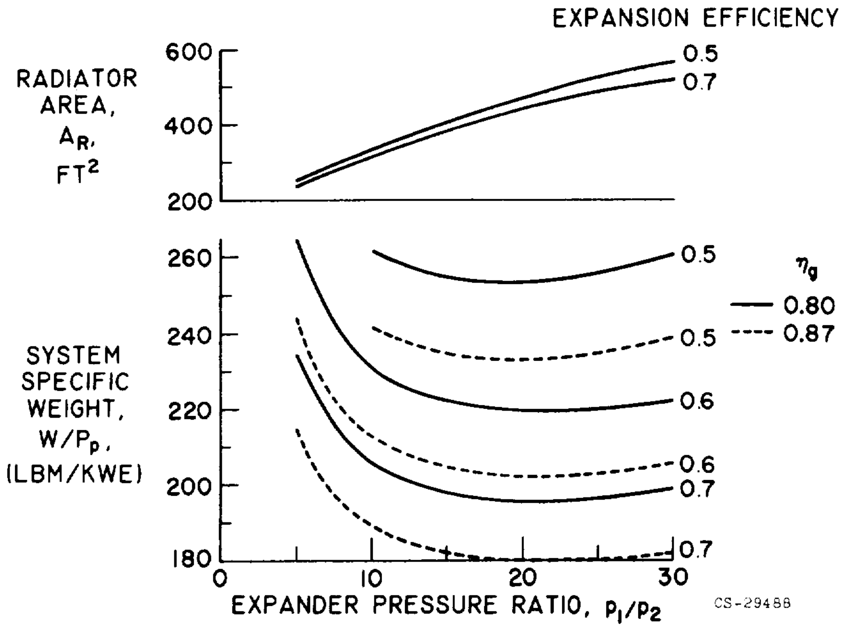

Fig. 5.

RESULTS

1. WEIGHTS FOR $p_1/p_2 = 20$, $\eta_{ex} = 0.6$

FIXED:	SOLAR COLLECTOR	186
	BOILER/HEAT STORAGE	260
	SPEED CONTROL	15
	STARTUP AUXILIARIES	65
	RECUPERATOR	40
	STRUCTURE AND MISC.	100
		666 LB
	RADIATOR	135
	EXPANDER	65
	ALTERNATOR	80
		280
	TOTAL WEIGHT	946 LB

	$\eta_g = 0.8$	$\eta_g = 0.87$
SPECIFIC WEIGHT (LB/KWE)	220	200
KVA TO PAYLOAD	4.3	4.7

2. RADIATOR AREA 450 SQUARE FEET

CS-29481

Fig. 6.