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STEAM ENGINE RESEARCH FOR SOLAR PARABOLIC DISH

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ABSTRACT

A steam engine design and experimental program is exploring the efficiency potential of a small 25 kW compound reheat cycle piston engine. An engine efficiency of 35 percent is estimated for a $700^{\circ}C$ steam temperature from the solar receiver.

BACKGROUND

The parabolic dish solar concentrator provides an opportunity to generate high grade energy in a modular system. Most of the capital cost is projected to be in the dish and its installation. Assurance of a high production demand of a standard dish could lead to dramatic cost reductions. High production volume in turn depends upon maximum application flexibility by providing energy output options, e.g. heat, electricity, chemicals and combinations thereof. Subsets of these options include energy storage and combustion assist.

Individual dish mounted engine generator sets represent a major market opportunity.

The Market

Projecting new product market potential is a risky business. Presuming success in meeting system cost and performance goals, dish-engine production has been studied in the 10,000 to 100,000 range of annual unit volume.

Selection of the best engine type from among the Brayton, Stirling and Rankine engines will have to wait for development results.

The Steam Rankine Engine

The positive displacement steam engine is an excellent fit in the component chain. High efficiency at moderate temperatures (55 to 59 percent of Carnot) yields high dish and receiver efficiencies as well. Engine efficiency is insensitive to load and ambient variations. A high efficiency 60 Hz alternator can be directly driven. Waste heat is accessible and at a useful temperature. Combustion assist and thermal storage coupling are straightforward.

All of the hardware is conventional in materials of construction and virtually already mass produced. The needed research is limited to the durability development of the hot cylinder, valves and long term water quality needs.

DESIGN STUDY

Two independent steam engine design studies were conducted for the DOE parabolic solar dish program managed by JPL. NASA LeRC as solar engine consultants contracted with Jay Carter Enterprises (1) and ourselves, Foster-Miller Associates (FMA) (2) for parametric and preliminary designs. The results were very similar in concept and performance potential.

The system arrangement places the high temperature and pressure engine components in the shadow of the receiver. The 60 Hz generator is directly driven. An atmospheric pressure condensor is mounted on the ground and cooled with a natural draft stack. FMA selected a drain down sump buried below the frost line. The water boost/emergency receiver coolant pump and electronics are also at ground level.

Compound expansion reheat cycles were chosen to maximize efficiency (Figure 1). One high pressure cylinder and one low pressure cylinder were predicted to be as efficient as any other combination of cylinder numbers.

Performance Analysis

FMA, combined with acquisition of the engine research group of Scientific Energy Systems, Inc., has developed a steam expander performance model. This work (3) is based on 5,000 hours of steam expander testing at an inlet temperature of 540°C. The important conculsions from this work were used to analyze the potential of cycle variations matched to specific expander designs (Figure 2, Table 1).

Trends of interest are the influences of temperature and pressure ratios. Increasing inlet temperatures result in increasing efficiency nearly proportional to the respective Carnot efficiencies. Increasing pressure ratios increase efficiency but with little benefit at the higher pressures. The limiting factors are the onset of cyclic heat transfer in the cylinders when the higher expansion ratios drive the exhaust temperature below the inlet steam saturation temperature and increasing friction losses in the larger low pressure cylinders required to handle the increasing exhaust volume.

Preliminary Design Study

The selected cycle and design approach were matched to a reheat steam receiver study conducted by AiResearch. The peak steam pressure and temperature were selected based on the demonstrated properties of stainless steels. ASME code properties for 316SS were judged to be adequate but Incoloy 800H, an iron based higher alloy, is suggested as a more cost effective material for the high pressure tubing.

The engine specifications (Table 2, Figure 3) calls for a low piston speed, 30 Hz expander of moderate displacement. Engine efficiency over the load range exceeds 34 percent.

Four features of the system design are unproven. The first issue is the validity of the performance model. The supporting data is derived from a lower temperature but higher stage pressure ratio engine. The extrapolation

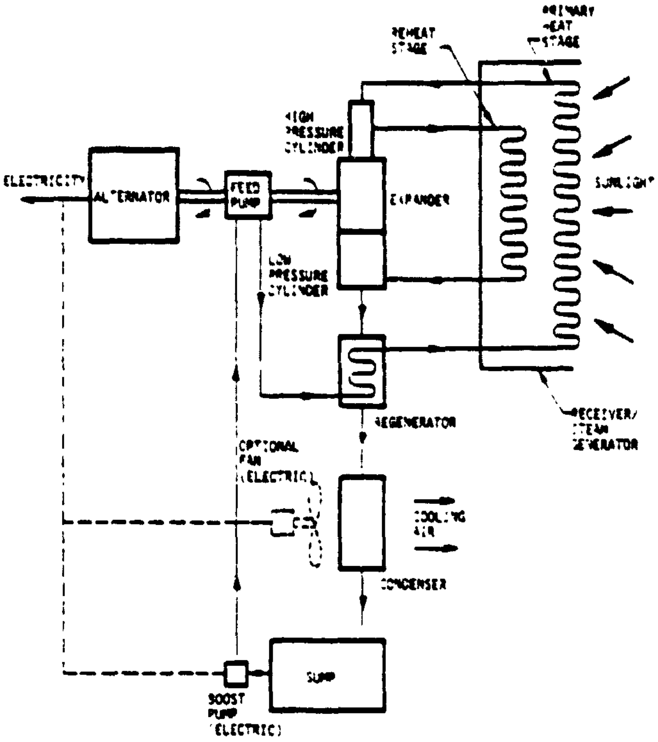

FIGURE 1. ENGINE SCHEMATIC

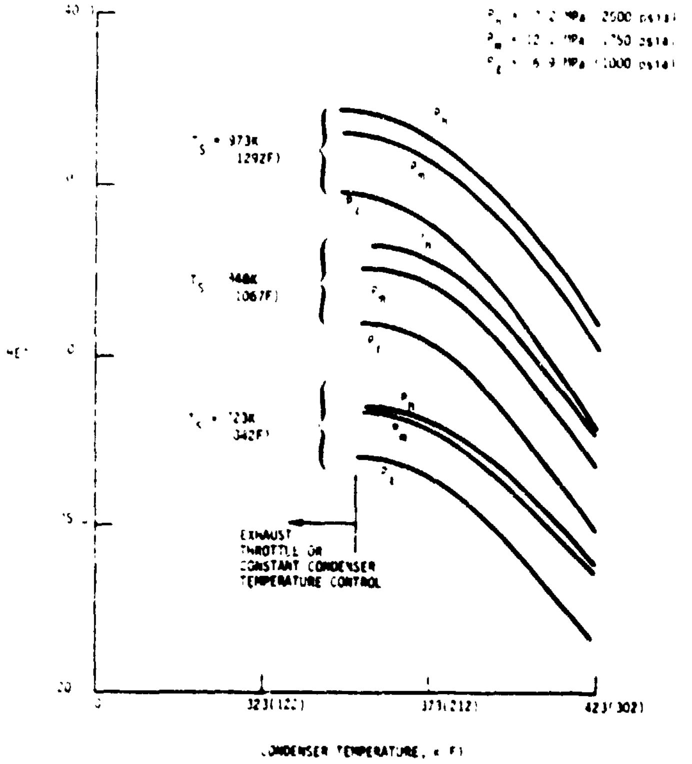

FIGURE 2 PARAMETRIC ENGINE EFFICIENCY

TAPLE 1. PARAMETRIC DESIGN DETAILS

Inlet Steam Temperature K (F)	Inlet Steam Pressure MPa (psia) 1st Stage	Inlet Steam Pressure MPa (psia) 2nd Stage	Mass Flow Rate g/s (lb/hr)	Displacement cm³ (in³) 1st Stage	Displacement cm³ (in³) 2nd Stage	Condenser Temperature K (F)	Feedwater Temperature K (F)	Auxiliary Power Required (kW)	Efficiencies (%) Prime Mover	Efficiencies (%) Heat Engine	Efficiencies (%) Overall Power Conversion	Ratio to Ideal Cycle
723 (841)	6.9 (1000)	1.4 (200)	21.4 (170)	81.5 (4.97)	1336 (81.5)	311 (101)	367 (201)	0.26	50.1	26.7	31.6	0.614
			20.3 (161)	77.2 (4.71)	1280 (78.1)	322 (120)	362 (193)	0.27	65.8	25.9	32.1	0.671
			19.8 (157)	75.4 (4.60)	1123 (68.4)	339 (150)	368 (203)	0.27	73.5	26.0	22.7	0.775
			20.9 (165)	79.4 (4.85)	719 (43.9)	372 (210)	403 (265)	0.30	84.7	20.7	23.7	0.890
			26.9 (212)	112.2 (6.85)	472 (28.8)	422 (300)	494 (430)	0.40	92.7	21.6	18.7	0.957
	12.1 (1750)		19.7 (156)	52.8 (3.22)	1220 (74.4)	311 (101)	368 (203)	0.46	60.3	26.7	22.3	0.631
			18.7 (148)	50.2 (3.06)	1145 (69.9)	322 (120)	364 (195)	0.44	66.6	27.4	21.3	0.687
			18.3 (145)	49.1 (3.00)	1036 (63.2)	339 (150)	370 (206)	0.43	73.8	28.2	24.0	0.775
			19.1 (152)	51.6 (3.15)	664 (40.5)	372 (210)	405 (270)	0.46	81.7	28.1	21.9	0.866
			25.7 (203)	68.8 (4.20)	419 (25.6)	422 (300)	494 (430)	0.61	91.1	23.8	20.3	0.875
	17.2 (2500)		19.9 (157)	40.3 (2.46)	1239 (75.6)	311 (101)	370 (206)	0.67	59.9	26.0	22.1	0.635
			18.9 (149)	38.3 (2.34)	1154 (70.4)	322 (120)	365 (198)	0.63	66.2	27.2	23.2	0.673
			18.4 (146)	37.4 (2.28)	1042 (63.6)	339 (150)	371 (209)	0.62	73.3	28.1	23.9	0.770
			19.6 (154)	39.3 (2.40)	668 (40.8)	372 (210)	407 (272)	0.67	83.0	27.9	23.7	0.835
			26.0 (206)	52.8 (3.22)	419 (25.5)	422 (300)	496 (433)	0.92	89.8	21.6	20.0	0.869
866 (1100)	6.9 (1000)	1.4 (200)	17.6 (139)	81.5 (4.97)	1293 (78.9)	311 (101)	401 (263)	0.26	61.0	28.3	24.1	0.660
			16.4 (130)	76.0 (4.64)	1109 (67.7)	322 (120)	390 (243)	0.22	68.7	29.9	25.6	0.723
			16.0 (127)	74.0 (4.52)	1069 (65.2)	339 (150)	394 (250)	0.22	76.2	30.0	26.2	0.794
			16.9 (134)	78.3 (4.77)	687 (41.9)	372 (210)	433 (319)	0.24	86.8	30.4	26.0	0.860
			24.0 (190)	111.5 (6.80)	456 (27.8)	422 (300)	539 (511)	0.31	93.1	21.2	21.2	0.859
	12.1 (1750)		15.5 (123)	52.5 (3.20)	1143 (69.8)	311 (101)	391 (244)	0.36	64.0	30.8	26.2	0.691
			15.1 (120)	51.1 (3.12)	1091 (66.6)	322 (120)	390 (243)	0.35	69.7	31.6	26.9	0.711
			14.8 (117)	50.0 (3.05)	989 (60.4)	339 (150)	395 (252)	0.35	76.4	32.0	27.[illegible]	0.780
			15.6 (124)	53.5 (3.26)	635 (38.8)	372 (210)	434 (322)	0.39	85.9	32	[illegible]7.5	0.861
			21.7 (172)	73.6 (4.49)	412 (25.1)	422 (300)	542 (516)	0.51	91.2	26	[illegible]2.[illegible]	0.851
	17.2 (2500)		15.2 (120)	40.6 (2.48)	1117 (68.2)	311 (101)	392 (247)	0.51	64.7	[illegible]	[illegible]5	0.690
			14.8 (117)	39.6 (2.42)	1067 (65.1)	322 (120)	392 (245)	0.49	69.4	3[illegible]	[illegible]2	0.731
			14.4 (114)	38.7 (2.36)	965 (58.9)	339 (150)	396 (253)	0.49	76.0	3[illegible]	[illegible]	0.787
			15.2 (120)	40.7 (2.48)	618 (37.7)	372 (210)	436 (325)	0.52	85.2	3[illegible]	[illegible]9	0.850
			20.6 (163)	55.1 (3.36)	344 (21.0)	422 (300)	540 (513)	0.71	89.7	27	[illegible]	0.851
973 (1292)	6.9 (1000)	1.4 (200)	12.7 (100)	73.9 (4.51)	1161 (70.8)	311 (101)	411 (280)	0.18	67.4	33.5	[illegible]	0.732
			13.6 (108)	72.8 (4.44)	1117 (68.2)	322 (120)	413 (283)	0.18	72.0	34.0	30.5	0.782
			13.3 (105)	71.9 (4.39)	1020 (62.2)	339 (150)	419 (294)	0.18	78.7	34.0	29.[illegible]	0.817
			14.5 (115)	78.5 (4.79)	670 (40.9)	372 (210)	426 (307)	0.20	87.0	33.8	28.7	0.868
			20.5 (162)	111.0 (6.77)	448 (27.3)	422 (300)	507 (453)	0.20	91.1	27.8	21.6	0.896
	12.1 (1750)		12.9 (102)	51.5 (3.14)	1212 (74.0)	311 (101)	422 (299)	0.30	66.7	34.8	29.8	0.732
			12.4 (98)	49.9 (3.05)	1031 (62.9)	322 (120)	416 (289)	0.29	73.5	35.6	30.4	0.796
			12.2 (97)	49.1 (3.00)	940 (57.4)	339 (150)	422 (299)	0.29	78.8	36.5	31.1	0.810
			13.3 (105)	53.3 (3.25)	621 (37.9)	372 (210)	473 (391)	0.32	86.1	35.7	30.3	0.850
			18.1 (143)	72.8 (4.44)	396 (24.2)	422 (300)	589 (601)	0.44	91.4	30.3	25.7	0.851
	17.2 (2500)		12.5 (99)	40.2 (2.45)	1057 (64.5)	311 (101)	423 (302)	0.42	66.8	35.1	30.0	0.732
			12.1 (96)	39.2 (2.39)	1003 (61.2)	322 (120)	418 (293)	0.40	72.4	36.4	30.9	0.790
			11.9 (94)	38.6 (2.36)	915 (55.8)	339 (150)	424 (304)	0.40	78.5	37.1	31.6	0.815
			12.9 (102)	41.7 (2.54)	602 (36.7)	372 (210)	475 (396)	0.44	85.7	36.1	30.9	0.854
			17.4 (138)	56.5 (3.45)	396 (24.2)	422 (300)	592 (605)	0.41	90.2	31.0	26.4	0.847

TABLE 2. PRELIMINARY DESIGN SPECIFICATION

Two cylinder, opposed, single throw crank
Single acting with crossheads
Compound expansion with reheat
Inlet temperatures 973K (1292F)
Atmospheric pressure condensing
Poppet valves, feedwater pressure actuated
Counterflow: 3% clearance volume
Carbon piston rings (no oil in steam)
Speed: 60π rad/s (1800 rpm) nominal - actual ≈1840 rpm
Stroke: 68 mm (2.67 in.)
Piston speed: 4.1 m/s (800 ft/min)

	Stage I	Stage II
Inlet pressure, MPa (lb/in.^{2})	12 (1750)	1.1 (153)
Bore, mm (in.)	43 (1.71)	149 (5.86)
Displacement, cm^3 (in.^{3})	100 (6.12)	1179 (72.0)
Maximum piston thrust, kN (lb)	17.0 (3816)	17.4 (3916)

Performance	Design Point	Maximum	Minimum
Electric output, kWe	21	26	13
Cut-off (%)	18.0	23.0	11.2
Flow rate, g/s (lb/hr)	16.8 (136)	21.0 (166)	11.1 (87.9)
Stage I MEP, MPa (lb/in.^{2})	4.2 (602)	5.1 (737)	2.7 (389)
Stage II MEP, kPa (lb/in.^{2})	363 (52.6)	444 (64.4)	234 (33.9)
IkW (IHP)	25.3 (33.9)	31.0 (41.5)	16.3 (21.9)
Expander efficiency (%)	87.9	87.4	82.8
Engine efficiency (%)	35.9	35.9	34.1
Alternator efficiency	92.1	91.6	90.8
Net electrical efficiency (%)	33.0	33.0	31.4

is done from basic principals starting from individually measured losses such as friction, pressure and heat transfer. A sensitivity analysis of each loss mechanism indicates that the net efficiency is rather forgiving. The reheat steam cycle is uniquely forgiving of internal losses by virtue of its highly regenerative nature (reheat recovery and feedwater heater) and low pumping power (1¼ percent).

The high steam temperature is unusual in a steam power system. Fossil fueled plants are primarily limited by sulfur corrosion on the air side. Internally, steam turbines are considered to be life limited by particulate erosion of the transonic blades and low cycle fatique of the massive rotors. The small piston engine is relatively free of these problems. A more severe problem *may* be the long term water quality that can be economically provided in the field.

Two design choices recommeded for development are dry lubricated piston rings and water pressure actuated hydraulic valves. Oil lubricated rings have been proven in steam with a 370°C face temperature in a 540°C expander. A similar environment could be obtained for this design using the hidden and cooled techniques used in Stirling engines with plastic rings. Avoidance of oil carryover and cylinder cooling losses suggests that dry lubrication is a valuable goal.

Similarly the valve actuation system could be accomplished with a cam and tappet system and/or a piston opened bash valve on the intake. It was felt that performance, complexity, life, and sealing would all benefit from feedwater pressure actuated pistons on the valve stems.

EXPANDER RESEARCH

FMA is starting to test the critical expander features of the preliminary design. Funding is provided by DOE through a small business program for Innovative Research on Solar Thermal Power Systems (4).

A prototype compound expander following the general principals and sizing results of the study has been built to test cylinder performance, dry (graphite) piston rings and water actuated valves.

The first build graphite piston rings are rectangular unbalanced snap types. Pressure balancing can be incorporated in later builds when basic pressure velocity wear data is obtained. Other alternative piston sealing methods such as hard on hard pairs and controlled leakage options can also be researched.

The valve actuation method is currently subject to Government patent disclosure. In principal feedwater pressure operates on alternate sides of a piston on the valve stem. A mechanically driven spool valve switches the water and is close coupled to the valve piston to minimize line dynamics. Squeeze film dampening is used on both ends of the valve stroke to control impact velocities.

The expander design is intended to grow into a field demonstration engine if the research results are encouraging. For example, the crankcase includes complete balancing shafts and accessory drive shafts.

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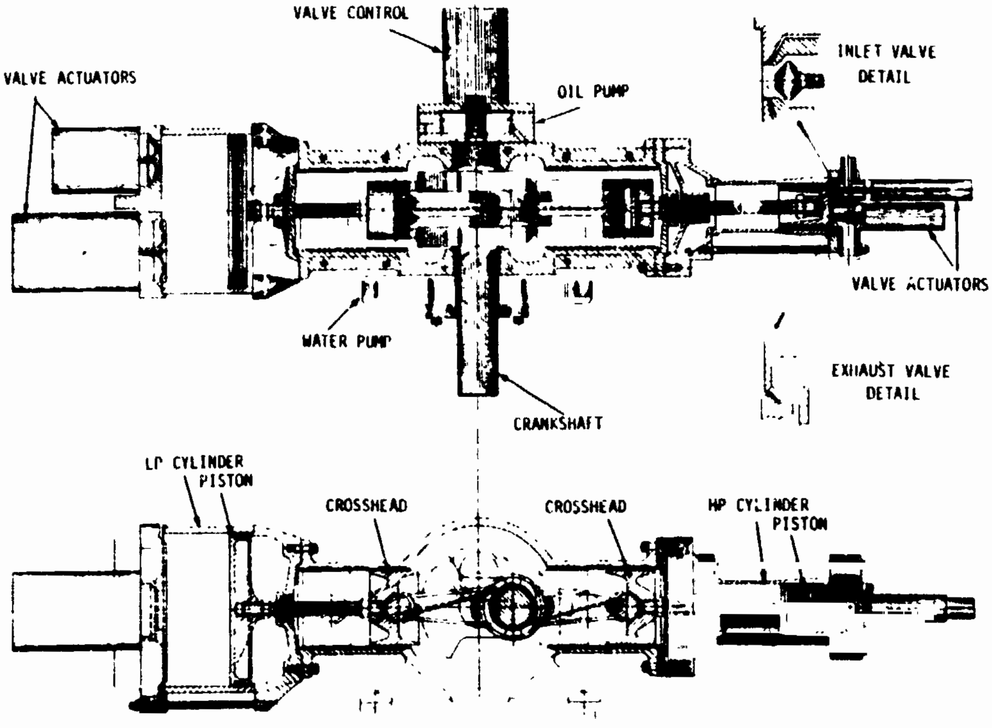

FIGURE 3. PRELIMINARY EXPANDER DESIGN