Title

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SUPERCRITICAL HEAT EXCHANGE FIELD TEST: FIELD PERFORMANCE DATA ON SHELL-AND-TUBE HEAT EXCHANGERS IN GEOTHERMAL SERVICE

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Supercritical Heat Exchange Field Test: Field Performance Data on Shell-and-Tube Heat Exchangers in Geothermal Service

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ABSTRACT

Presented are results from a binary-cycle test loop. Results cover loop operational problems, overall heat transfer coefficients, LMTD's, and duties for six primary heaters in counterflow having brine in the tubes and hydrocarbon in the shells, and for a condenser. Fluids tested were isobutane and mixtures of isobutane/isopentane; each heated at supercritical conditions and condensed at subcritical conditions.

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Introduction

Although the geothermal binary cycle is conceptually simple, practical problems surround its implementation. Two important problem areas are heat exchangers and operation of the complete cycle loop.

The central issue for the primary heaters is adequate predication of their performance with a supercritical hydrocarbon, particularly in the near critical region where the thermo-physical properties show marked nonlinear behavior. The central issue for the condenser is that much of the steam condenser technology is not applicable. The size of the condensers required for a commercial power plant exceeds the data base for process condensers.

The central issue for the complete binary loop is its stability, particularly when traversing from subcritical to supercritical conditions, and the performance of other loop equipment as concerns potential problem areas in design, reliability and control.

Experimental

To obtain data in the above-mentioned problem areas, a test loop (Figure 1) was constructed at the U.S. Department of Energy Geothermal Test Facility (GTF) at East Mesa in California's Imperial Valley. Figure 1 is a schematic of the test loop. The test unit consisted of three fluid loops: brine, hydrocarbon, and cooling water. The three loops were interconnected through the primary brine/hydrocarbon heat exchanger train and the hydrocarbon/cooling water condenser-subcooler train. The heat load was rejected to the atmosphere through a wet cooling tower. The high-pressure (heater) portion of the hydrocarbon loop was separated from the low-pressure (condenser) portion by a pressure-reducing valve in lieu of a turbine.

The primary brine/hydrocarbon heat exchanger train consists of six exchangers, both sides in series and in counterflow, with brine in the tubes and hydrocarbon in the shells. Table 1 lists the main features of the exchangers, and Table 2, the main features of the condenser. The GTF well Mesa 6-2 used a downhole pump to supply the brine. The GTF cooling tower supplied the cooling water.

Hydrocarbons were from industrial suppliers in commercial grades used primarily as aerosol propellants. Mixtures were made at the test site by mixing isobutane and isopentane. Three mixtures were run, commercial isobutane, 90/10 (mole %) isobutane/isopentane, and 80/20 isobutane/isopentane.

The shell side (hydrocarbon) of all exchangers and their inter-connecting piping were chemically cleaned to a rust-free state just prior to the start of testing. The metal surfaces retained their cleaned condition throughout the testing as verified by periodic visual inspections. The tube side of all exchangers were periodically cleaned by hydrolancing. The heat exchanger tubes exposed to the geothermal brine scaled little, whereas cooling water tube scaling in the condenser varied greatly with operating conditions.

Data were recorded by hand; temperatures were taken from mercury-in-glass thermometers, pressures from Ashcroft precision gauges, and flow rates from orifice plate, venturi, and turbine flow meters. All instrumentation was calibrated against traceable standards. Hydrocarbon fluid analysis was by gas chromatography.

For the primary heaters, data station locations were: temperatures of tube side and shell side fluids at the entrance and exit of each exchanger, shell side pressures at the entrance and exit of each exchanger, and tube side pressures at the entrance, midpoint, and exit of the heat exchanger train. Valving in the brine supply to the primary heat exchanger train allowed either four, five, or six exchangers to be in service.

For the condenser-subcooler, data stations are temperature and pressure at the entrance and exist of each exchanger for both shell side and tube side.

Flow rate data stations were: venturi and orifice plate at the primary heat exchanger train exit for the tube side (brine), turbine flow meter and orifice plate at the primary heat exchanger train entrance for the shell side (hydrocarbon), and separate turbine flow meters for the cooling water to the condenser and subcooler. Additional details are given elsewhere.[1, 2]

Data Analysis

Analysis of the energy transferred as heat within a heat exchanger is given by:

$$Q = U*A*\Delta T_m, \qquad (1)$$

where Q is the duty, U is the overall heat transfer coefficient, A is the cross-sectional area perpendicular to the heat flux, and T_m is the mean temperature difference.

For a shell-and-tube exchanger, where the heat capacity, C_p, of both fluids is constant, and U is constant, Equation (1) may be written as

$$Q = U*A*LMTD, \tag{2}$$

where LMTD is the log-mean-temperature difference:

$$LMTD = (T_a - T_b)/\ell n\ (T_a/T_b) \tag{3}$$

with $T_a = T_{1,in} - T_{2,out}$ $\quad T_{1,in} > T_{2,out}$

$T_b = T_{1,out} - T_{2,in}$ $\quad Y_{1,out} > T_{2,in}$

For a heat exchanger where C_p for both fluids is constant and U is constant over the entire exchanger, the LMTD may be computed from the entrance and exit temperatures. For a heat exchanger where C_p for one or both fluids is not constant, the exchanger is subdivided, or zoned, into widths over which C_p and U are sensibly constant. Equation (2) for a zoned analysis becomes for the i^{th} zone,

$$Q_i = (UA)_i*LMTD_i. \tag{4}$$

Primary Heaters

Equation (4) was applied to the primary heat exchanger train as follows: The entire heat exchanger train was treated as one exchanger composed of experimental zones represented by the number of series connected exchangers. Equation (4) was applied to each zone. The duty Q_i was set equal to the brine duty. The $LMTD_i$ was computed from the measured terminal temperatures.

For each zone, we computed

$$(UA)_i = Q_i/LMTD_i. \tag{5}$$

From the n zones, the total duty, Q_{tot}, was computed as

$$Q_{tot} = \sum_{i=1}^{n} Q_i \qquad n = 4, 5, \text{ or } 6. \qquad (6)$$

The LMTD for the entire heat exchanger train was computed as

$$LMTD = Q_{tot}/ \sum_{i=i}^{n} (UA)_i \qquad n = 4, 5, \text{ or } 6. \qquad (7)$$

Finally, the overall heat-transfer coefficient, U_f, was computed as

$$U_f = Q_{tot}/((n*A_i)*LMTD), \qquad (8)$$

where A_i is the area of one exchanger

The results are listed in Tables 3. Unless otherwise noted, the results are for six exchangers in series. The tabulated results for each condition are the average of six to eight data scans. Overall heat balances for each scan were with $\pm$ 3%. The subscripts "in" and "out" refer to entrance and exit values for the entire heat exchanger train.

The reader is cautioned that the tabulated U_f and LMTD should be used with the following caveat. The experimental region is one of high nonlinear C_p for the hydrocarbon; consequently, a zoned analysis is required. Subdivision into experimental zones, however, is inadequate for the high-temperature half of the exchanger train. The resulting U_f and LMTD are intended as estimates of performance. Further, no effort was made to satisfy the momentum balance using the shell side and tube side pressure drop data. These deficiencies are addressed elsewhere.

Condenser

A modified form of Equation (2) was applied to the condenser:

$$Q = U*A*MTD, \tag{9}$$

where Q, U, A, have the same meaning as before, and MTD is the mean temperature difference.

The duty, Q, was set equal to the water duty. The area, A, was taken as the tube area listed in Table 2, except for the half-bundle tests, where external valving allowed only a single tube pass, cutting the heat transfer area in half.

The MTD was computed as

$$MTD = F * LMTD, \tag{10}$$

where LMTD is the log-mean-temperature difference defined by Equation (3), and F is a correction factor defined as

$$F = -a/N_{tp} * \ n\ (1 + \ n\ (1 - b)/r), \qquad (11)$$

N_{tp} = 1 (number of tube passes),

$$r = \frac{T_{hc,sat,in} - T_{hc,sat,out},}{T_{cw,out} - T_{cw,in}},$$

$$p = \frac{T_{cw,out} - T_{cw,in}}{T_{hc,sat,in} - T_{cw,in}},$$

$$a = (1/(r - 1) * \ n\ ((1 - p)/(1 - b)),$$

$$b = p * r,$$

and $T_{hc,sat}$ is the hydrocarbon vapor-liquid saturation temperature at the experimental condenser pressure, and T_{cw} is the cooling water temperature.

The results are listed in Tables 4. The tabulated results for each test condition are the average of six to eight data scans. Overall heat balances for each scan were within $\pm$ 3%.

Fluid Properties

The geothermal fluid was a low-salinity brine ($\sim$1400 ppm (NaCl(aq)) and consequently was treated as pure water with fluid properties computed from the Keenan and Keyes[3] equation-of-state for water.

Hydrocarbon properties were computed from a computer code jointly developed by The National Bureau of Standards and LBL. The computer code employs extended corresponding states.

Operational Problems

During testing various operational problems arose. All were solved and are chronicled elsewhere.[1,2] The important problems were:

1. The shell side of the exchangers was successfully cleaned using a HCl/ammonium bifluoride-ammonium citrate solution which gave excellent results.

2. Hydrolancing of the exchanger tubes proved quick, simple, and gave excellent results.

3. Suspended matter swept up by the circulating hydrocarbon was effectively removed by filtering.

4. Instrument performance was excellent with no failures in flow meters, thermometers, pressure gauges, or controllers.

5. Leaks in the heat exchangers occurred during the testing. All leaks were from weld failures at the tube/tube-sheet interface. All leaks were repaired in the field by heli-arc welding.

6. Analysis of the hydrocarbon taken from the test loop during testing showed no detectable levels of water.

7. The test loop was stable for all test conditions encountered, both for subcritical and supercritical operations, and for traversing between either mode.

Conclusions:

Experimental heat transfer data from a geothermal binary cycle test loop operating under field conditions common to proposed commercial installations. An experimental zone analysis of the heater data and analysis of the condenser data provided overall heat transfer coefficients and mean temperature differents which can serve as bench marks for future commercial designs.

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2. L.F. Silvester and P.T. Doyle, "Analysis of Field Performance Data on Shell-and-Tube Heat Exchangers in Geothermal Service", LBL-14160, Lawrence Berkeley Laboratory, University of California, Berkeley, March 1982.

3. J.H. Keenan, F.G. Keyes, P.G. Hill, and J.G. Moore, Steam Tables, Wiley-Interscience, New York, New York, 1978.

SUPERCRITICAL HEAT EXCHANGE FIELD TEST (SHEFT)

TEST FACILITY SCHEMATIC DIAGRAM

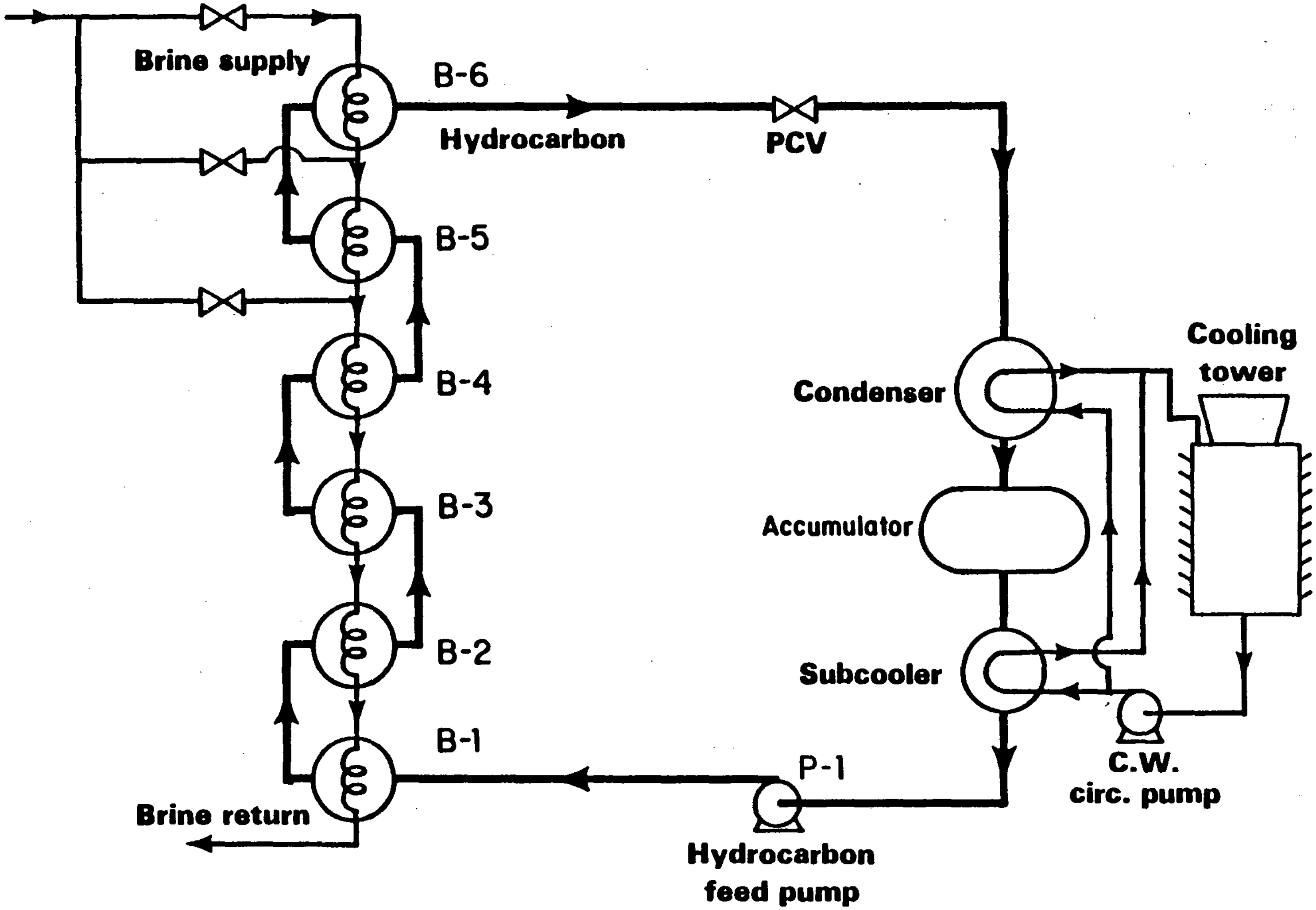

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Figure 1. Schematic of Supercritical Heat Exchanger Field Test Apparatus.

Table 1. Primary heat exchanger details

No. of tubes per exchanger:	62
No. of passes:	1 shell side, 1 tube side
Tube length:	24 ft
Tube size:	3/4 in O.D., 16 BWG.
Tube material:	carbon steel (SA-214)
Tube pitch:	15/16 in., triangular array
Shell I.D.:	8 3/4 in.
Baffle spacing:	12 in.
Baffle cut:	13/16 in. from center line
Area per exchanger:	292 ft^2
Number of exchangers:	6

Table 2. Condenser details

No. of tubes:	332
No. of passes:	1 shell side, 1 tube side[a]
Tube length:	24 ft
Tube size:	3/4 in O.D., 14 BWG
Tube material:	carbon steel (SA-214)
Tube pitch:	15/16 in., triangular array
Shell I.D.:	22 in.
Baffles:	Supports

[a]Side by side.

Table 3. Primary Heater Data Analysis -- Experimental Zone

T(Br-in) (°F)	T(Br-out) (°F)	M-Br (lbs/hr)	T(Hc-in) (°F)	P(Hc-in) (psia)	T(Hc-out) (°F)	P(Hc-out) (psia)	M-Hc (lbs/hr)	Duty (Btu/hr. 10^{-6})	U_f (Btu/hr-Ft^2-°F)	LMTD (°F)
Commercial Isobutane										
339	205	93200	141	667	314	603	74585	12.77	392	18.6
339	218	93366	131	654	329	601	60694	11.56	364	18.1
336	253	92785	135	645	336	621	43016	8.07	290[a]	23.9
339	208	102357	152	676	311	599	83178	13.76	430	18.2
343	202	99136	152	652	308	571	86598	14.27	427	19.0
343	213	101870	143	639	326	572	71250	13.41	413	18.5
344	239	101006	138	636	341	571	53535	10.89	334	18.6
345	277	101605	137	607	345	585	35216	7.25	222[a]	28.0
345	206	101684	157	656	311	573	86910	14.41	439	18.7
344	206	95408	161	633	307	552	85276	13.54	423	18.3
345	213	95938	147	617	329	550	69123	12.94	395	18.7
338	201	64052	146	584	310	552	53420	8.95	306	16.7
344	207	97556	162	633	309	552	84360	13.67	425	18.3
Nominal 90/10 Isobutane/Isopentane										
346	201	94843	120	685	312	640	80873	14.04	391[a]	30.7
342	202	93051	119	656	323	600	70024	13.30	380	20.0
342	220	80142	118	637	339	603	48776	9.96	327[b]	17.4
343	192	98683	130	651	307	571	84678	15.22	407	21.3
346	203	94921	118	639	318	588	68873	13.85	393	24.1
341	204	70876	124	604	316	577	49646	9.86	325	20.8

Note: Br = brine; Hc = hydrocarbon.

[a]Four exchangers in series.

[b]Five exchangers in series.

Table 3 continued

T(Br-in) (°F)	T(Br-out) (°F)	M-Br (lbs/hr)	T(Hc-in) (°F)	P(Hc-in) (psia)	T(Hc-out) (°F)	P(Hc-out) (psia)	M-Hc (lbs/hr)	Duty (Btu/hr. 10^{-6})	U_f (Btu/hr-Ft^2-°F)	LMTD (°F)
Nominal 90/10 Isobutane/Isopentane										
343	193	100400	122	626	310	552	78884	15.31	411	21.3
343	218	98397	121	630	329	576	63080	12.65	385[b]	22.5
341	219	75497	135	593	330	566	48097	9.42	325[b]	19.9
Nominal 80/20 Isobutane/Isopentane										
344	193	96247	126	675	313	599	90590	14.88	391	21.7
345	198	96656	123	684	314	622	88682	14.52	386[a]	25.7
345	204	97186	120	610	317	643	86962	14.01	37[b]	32.0
342	202	85599	127	654	317	603	72851	12.31	352	20.0
344	230	86270	130	635	335	599	53268	10.10	337	17.1
345	193	96560	135	656	307	574	94181	14.96	395	21.6
345	210	96515	133	635	319	575	75374	12.39	386	19.6
343	223	85921	129	612	320	574	55902	10.58	341	17.7
345	196	100502	141	637	303	549	96802	15.20	409	21.2
345	208	100389	130	616	317	550	77817	14.05	397	20.2
346	230	100746	123	603	339	550	58054	11.92	360	18.9
345	206	100603	135	675	316	603	85924	14.26	394	20.6

Note: Br = brine; Hc = hydrocarbon.

[a]Four exchangers in series.

[b]Five exchangers in series.

Table 4. Condenser Data Analysis

T(cw-in) (°F)	T(cw-out) (°F)	M-Cw (lbs/hr)	P(cond) (psia)	T(Hc-in) (°F)	T(Hc-out) (°F)	M-Hc (lbs/hr)	Duty (Btu/hr. 10^{-6})	U_f (Btu/hr-Ft^2-°F)	MTD (°F)
Commercial Isobutane									
110	131	496945	205	212	174	81565	10.50	155	52
111	127	479748	172	171	158	62907	7.59	152	39
80	99	376760	116	239	125	39130	7.08	157	35
87	113	374758	159	171	152	76964	9.65	146	51
84	107	373982	140	215	140	53612	8.43	148	44
107	127	441127	188	206	165	67332	8.88	144	48
116	136	432522	206	204	174	69854	8.57	139	48
98	113	507173	203	198	173	62193	7.48	178[a]	67
Nominal 90/10 Isobutane/Isopentane									
119	141	399152	206	211	181	70387	8.71	130	52
102	125	412942	183	200	168	72886	9.43	131	56
95	116	423201	162	207	155	62110	8.85	134	51
79	97	370305	108	221	127	38770	6.63	129	40
82	117	193197	136	205	143	44417	6.76	120	43
119	139	399854	202	212	177	63877	8.08	126	49
99	116	484015	202	207	177	64766	7.98	170[a]	72
Nominal 80/20 Isobutane/Isopentane									
113	139	393314	205	210	187	78232	9.81	119	64
98	123	403376	175	213	173	72125	10.20	120	65
84	122	262970	161	210	167	69628	9.99	115	67
78	115	243898	141	191	156	51925	8.88	111	62
76	90	434426	90	227	113	33270	6.30	145	34
82	103	433044	131	239	133	48768	9.03	161	43
106	136	387230	206	243	190	83110	11.53	113	70
94	115	486431	219	234	196	79981	9.8	160[a]	95

Note: cw = cooling water; Hc = hydrocarbon; cond. = condenser.

[a]Half bundle test.

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