Title

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THE IMPORTANCE OF THE SPECIFIC HEAT ANOMALY IN THE DESIGN OF BINARY RANKINE CYCLE POWER PLANTS

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ABSTRACT

The transposed critical temperature (TPCT)[*] is shown to be an extremely important thermodynamic property in the selection of working fluids and turbine states for geothermal power plants operating on a closed organic (binary) Rankine cycle.

When the optimum working fluid composition and process states are determined for specified source and sink conditions, turbine inlet states consistently lie adjacent to the working fluids' TPCT line for all resource temperatures, constraints, and cost and efficiency factors investigated.

INTRODUCTION

Key determinants in Rankine cycle performance are the working fluid and turbine states. Although the steam Rankine cycle has been applied worldwide for over 75 years, little useful information has developed from this technology for general Rankine cycle working fluid selections. Geothermal development interest has provided stimuli for more general investigations. Recent binary cycle research has identified some desirable thermodynamic characteristics of organic working fluids, but controversy still exists regarding optimum cycle configurations and process states. Thermodynamic criteria have been lacking for selecting the working fluid and turbine states for even the simple organic Rankine cycle for specified source and sink conditions.

The objective of this report is to present an overview of recent LBL research (Pope and Doyle, 1980), which provides new insight for working fluid and turbine state selections for the geothermal binary Rankine power cycle.

LBL BACKGROUND IN GEOTHERMAL POWER PLANT STUDIES

With funding from the U.S. Department of Energy (DOE), Division of Geothermal Energy (DGE)[*], LBL is developing a relatively general thermodynamic cycle simulator, GEOTHM (Green, et al, 1977). The GEOTHM Code is coupled with non-linear optimization routines, which permit thermodynamic energy conversion systems of specified net power to be optimized for various design objectives. GEOTHM is modular in construction permitting various types[**] of thermodynamic cycles to be design optimized. GEOTHM also contains an extensive fluid properties library. An up-to-date description of LBL's system analysis capabilities is contained in a forthcoming DOE/DGE Geothermal SOURCEBOOK (Kestin, et al, 1979).

WHAT IS THE SIGNIFICANCE OF THE TRANSPOSED CRITICAL TEMPERATURE?

In the course of developing Section 8.2 of the SOURCEBOOK, we noted that the TPCT of a binary Rankine cycles' working fluid might play a key role in the selection of optimum turbine operating states. Specifically it was noted that when fuel costs (of pure working fluid cycles) clearly dominated, the cycles' optimum turbine inlet states fell on the TPCT line.

We further suggested (Kestin, 1979, Section 8.2.9.6) that if the working fluid's composition was simultaneously optimized with the six independent thermodynamic state parameters of the geothermal binary Rankine cycle, improved thermodynamic and economic performance might be obtained when both plant and fuel costs were material, but neither dominated. This has been repeatedly verified.

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[*] The Transposed Critical Temperature line is defined as the locus of points in a fluids' supercritical vapor region where the specific heat is a maximum.

[*] Utilization Technology Branch (Mr. Clifton B. McFarland, Chief).

[**] With modest code changes -- user constraints, penalty functions, etc.

DISCLAIMER

MIXTURE WORKING FLUIDS - PREVIOUS WORK

The potential advantages of hydrocarbon mixtures as working fluids for the geothermal-binary-Rankine cycle have been emphasized by Starling (1976) and Ben Holt (Roberts, 1976). A recent document (Iqbal et al, 1978) contains an informative summary of the potential advantages and disadvantages of mixtures, and possible working fluid selection criteria, including the fluid's I-factor.

LBL INVESTIGATIONS OF MIXTURE BINARY RANKINE CYCLES

LBL has investigated (Pope and Doyle, 1980) the thermodynamic characteristics of busbar cost optimized mixture-binary-Rankine geothermal cycles using the isobutane/isopentane (iC_4/iC_5) hydrocarbon system over a range of potentially applicable resource temperatures. This mixture system has a "retrograde" vapor saturation boundary on temperature-entropy coordinates with an I-factor less than 1.0, and therefore, may be regarded as a sub-set of all potentially attractive candidate working fluids for the studied resource temperature range. The Starling specific MBWR (1975) equation of state (Starling and Fish, 1976) was used by LBL for this initial study because it existed. Because its accuracy has been questioned (Silvester, 1978), and the fact that brine price and equipment capital costs are rapidly escalating, the LBL mixture studies were conducted on a simple binary power plant system with a number of practical simplifying assumptions (see Pope and Doyle, 1980).

SCOPE OF THE LBL MIXTURE BINARY CYCLE STUDIES

The geothermal system studied was the conventional simple binary cycle power plant coupled to an idealized geothermal resource (see Kestin, 1979, Section 8.2.11). The power plant assumed single phase brine production, shell-and-tube heat exchangers, and forced draft, wet cooling tower heat rejection. All major system parasitic losses were characterized. The cycles were investigated over sub-critical and supercritical regimes assuming the iC_4/iC_5 system for the resource temperature range between 170°C and 200°C. Plant and Field (fuel) sub-system cost and efficiency factors were varied over wide limits (up to a factor of 5). For our Baseline System, sub-system unit capital costs, fuel costs, efficiency factors, and financial factors were normalized to the Baseline Heber Binary plant of the Holt/Ghormley study (Roberts, 1976).

Three general system constraint conditions were investigated:

1. Turbine inlet allowed anywhere outside the two-phase vapor region.
2. Turbine inlet entropy $\geq$ maximum saturated vapor entropy.
3. Brine return temperature $\geq$ 344.26 K (160 F).

All the 50 MWe (Net) power plants were optimized for minimum cost of energy at the busbar assuming the following seven independent thermodynamic system parameters as "optimizable parameters":

1. turbine inlet temperature, T_T,
2. turbine inlet pressure, P_T,
3. condensing (bubble point) temperature,
4. isobutane mole fraction,
5. primary heater pinch point temperature difference,
6. condenser pinch point temperature difference, and
7. cooling tower approach temperature difference.

RESULTS

Highlights of some of the interesting new results follow. We find that optimized geothermal binary power plant designs using the iC_4/iC_5 system ($170°C \leq T_{RES} \leq 200°C$) and single phase brine production exhibit the following general thermodynamic characteristics:

A. Working fluid cycles are supercritical.

B. The iC_4 mole fraction decreases monotonically with resource temperature but also depends upon other variables.

C. Turbine inlet states are extremely close to the working fluids' TPCT line with a constant reduced P, T displacement which depends only upon constraint assumptions.

D. Turbine expansion is dry with a minimum of exhaust superheat (consistent with the I-factor of the selected mixture and turbine state constraints).

E. The utilization efficiency is virtually constant (independent of resource temperature) and higher than achieved from cost optimized cycles with either pure component.

F. Moist turbine expansion is extremely detrimental to system economics for power plant cycles utilizing these retrograde (on T-S coordinates) fluids.

As the result of A, B, C, and D the cost optimized iC_4/iC_5 simple binary cycle systems appear to obey similitude rules on reduced thermodynamic coordinates and correlate over all resource temperatures considered. The reduced turbine states exhibit extremely small sensitivities to sub-system cost and efficiency assumptions for the imposed constraint conditions.

Figure 1 illustrates the optimum mixture composition as a function of resource temperature for un-constrained designs and for four resource temperatures with a brine return temperature constraint. Also shown on the plot are Ben Holt's conceptual design recommendations (Roberts, 1976) for initial Heber temperature conditions (Holt suggested a different hydrocarbon system for end-of-life conditions). It is clear from Figure 1 that the optimum composition depends upon resource temperature and brine return temperature constraints. Additional calculations disclosed that the optimum composition is also a function of turbine inlet constraints and the unit fuel cost, but is little affected by other sub-system unit capital cost or efficiency factors (Pope and Doyle, 1980).

By far the most interesting and potentially useful result of this study is the fact that optimum turbine inlet states on reduced coordinates lie extremely close to, and at a constant displacement from, the fluids' TPCT line. This behavior is illustrated for busbar cost optimized cycles in Figure 2 for $(T_T/T_{cr})_{OPT}$ and Figure 3 for $(P_T/\ P_{cr})_{OPT}$. In Figure 2, note that the reduced optimum turbine inlet temperature, $(T_T/T_{cr})_{OPT}$, lies consistently within 0.8% of the reduced TPCT (at the optimum turbine inlet pressure) for all resource temperatures, all cost and efficiency assumptions, and all constraints conditions adopted in this study. Similar behavior for the optimum turbine inlet pressure is illustrated in Figure 3. Again the displacement is relatively constant on reduced coordinates, and variations up to a factor of 5 in sub-system unit costs have no significant influence.

The obvious importance of the Transposed Critical Temperature on the selection of working fluids and turbine states for Rankine cycle energy conversion systems has never been previously reported to our knowledge.

The busbar energy cost Design Surface (design objective) for optimized mixture binary Rankine cycles can be visualized in the 3-D plot, Figure 4. In Figure 4 the computed busbar energy cost is plotted as a function of the turbine inlet temperature and pressure.*

The values of P_T and T_T along the sharp "trough" (the Global Minimum busbar cost region) are virtually coincident with the TPCT line of the optimum mixture. The relatively flat operating region on the left of Figure 4 corresponds to slightly sub-critical and slightly supercritical turbine inlet states below the TPCT to the right of the Critical Point in the superheated vapor region. The region on the right side of Figure 4, where the busbar energy cost rises abruptly, corresponds to turbine inlet states immediately above and/or to the left of the TPCT line (on P-h coordinates) which would result in expansion (by one or more exhaust stages) into the two-phase vapor region of the selected optimum mixture. Figure 4 clearly shows the severe system economic penalties associated with reduced turbine efficiency due to wet expansion.

The TPCT line, defined by the peaks in the working fluids' anomalous specific heat, and the vapor saturation boundary (of the optimum working fluid), therefore, clearly define the limits of the economically desireable operating region for the expander of the binary Rankine cycle.

CONCLUSIONS

- The Transposed Critical Temperature is an important thermodynamic property which should be considered in the selection of working fluids and operating states for geothermal binary Rankine cycles.

- A high priority should be placed on the development of a new equation-of-state for hydrocarbon mixtures. Extended Corresponding States formulations appear promising.

- Although this study was limited to simple binary-Rankine-cycle-geothermal power plants with a single mixture system and a limited resource temperature range, the TPCT results suggest broader potential applicability.

- Mixture-binary-Rankine cycles appear to offer significant utilization efficiency and economic advantages over pure fluid cycles, and consequently, could play an important role in electric power development of moderate temperature geothermal resources.

ACKNOWLEDGEMENT

We acknowledge the valuable contributions of H.S. Pines in the development of the TPCT cycle concept and for assistance in recent GEOTHM code improvements which made this study possible.

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*The other independent system state parameters (optimizable parameters) have been fixed at their computed optimum values for producing this plot (see Kestin, 1979, Section 8.2.9.3).

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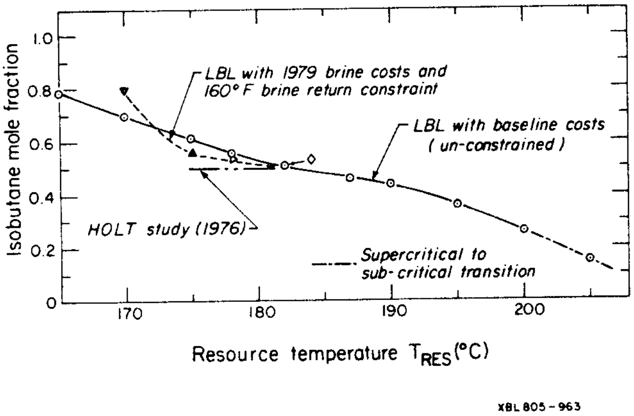

FIG. 1 Computed optimum iC_4 mole fraction as a function of resource temperature. The optimum composition also depends on turbine constraints (not shown).

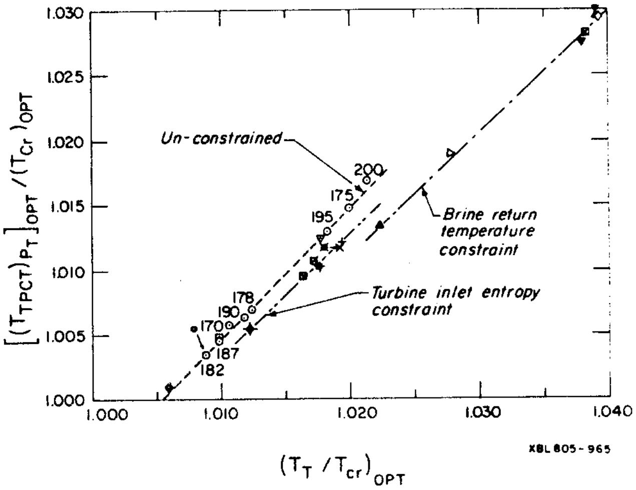

FIG. 2 Correlation between the temperature on the TPCT line (at the optimum turbine inlet pressure) and the optimum turbine inlet temperature for busbar cost optimized iC_4/iC_5 mixture geothermal-binary-Rankine-cycle power plants.

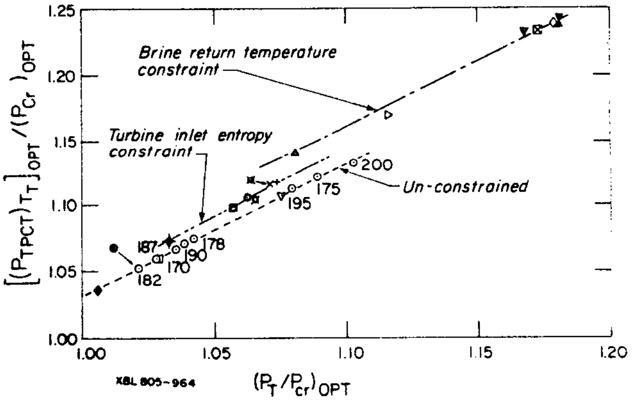

FIG. 3 Correlation between the pressure on the TPCT line (at the optimum turbine inlet temperature) and the optimum turbine inlet pressure.

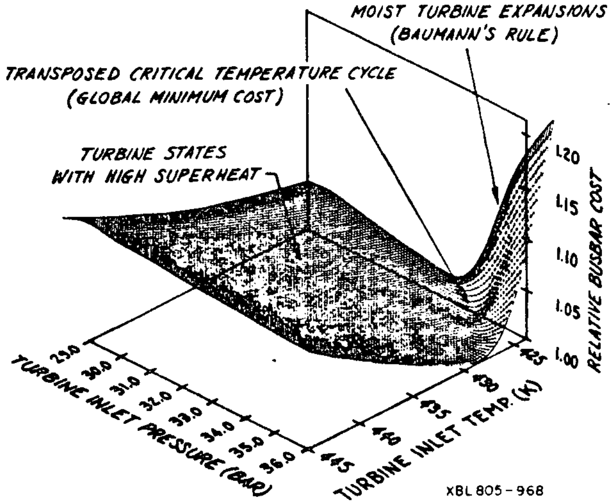

FIG. 4 Relative busbar energy cost design surface.