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PATENT CLEARED

GEOHERMAL HEAT CYCLE RESEARCH
SUPERCRITICAL CYCLE WITH HORIZONTAL COUNTERFLOW CONDENSERG. L. Mines
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The Heat Cycle Research Program, which is being conducted for the Department of Energy, has as its objective the development of the technology for effecting the improved utilization of moderate temperature geothermal resources. To meet this objective, the program has as one of its goals to improve the performance of geothermal binary cycles to levels approaching the practicable thermodynamic maximum. In pursuit of this goal, tests are being conducted at the Heat Cycle Research Facility located at the DOE Geothermal Test Facility, East Mesa, California. The current testing involves the investigation of binary power cycle performance utilizing mixtures of non-adjacent hydrocarbons as the working fluids, with supercritical vaporization and in-tube condensation of the working fluid. In addition to the present test program, preparations are being made to investigate the binary cycle performance improvements which can be achieved by allowing supersaturated vapor expansions in the turbine. These efforts are anticipated to verify that through the utilization of these advanced power cycle concepts and allowing the supersaturated turbine expansions, improvements of up to 28% in the net geofluid effectiveness (net watt hours plant output per pound of geofluid) over conventional binary power plants can be achieved. Results are presented for the recent testing including those tests examining the performance of the countercurrent condenser at different tube inclinations. Performance of the heaters and the condenser in a vertical orientation can be predicted well with existing methods and data. The condenser in its near horizontal orientation performs slightly worse than in its vertical orientation. Some problems have been encountered in predicting the performance in the horizontal orientation. There is no evidence of departure from integral condensation in either orientation. Indications to date are that the turbine performs with no degradation in performance when its expansion is "through" the two-phase region.

Background

The purpose of the Heat Cycle Research Program is to develop the technology which will result in more effective utilization of moderate temperature geothermal resources; the major emphasis of the program has been directed toward the improvement of the performance of geothermal binary cycles, in terms of the net geofluid effectiveness, to the practicable thermodynamic maximum. Investigations currently in progress

are examining advanced plant concepts which include the utilization of supercritical vaporization of working fluid mixtures of non-adjacent hydrocarbons and counterflow in-tube condensing in an organic Rankine cycle. Previous analytical studies^{1,2,3} have shown that utilization of these advanced plant concepts can provide improvements of up to 20% in the net geofluid effectiveness over conventional geothermal binary power plants in the 350 to 400 °F resource temperature range. The present test program is attempting to verify the assumptions made in these studies, i.e., the "state-of-the-technology" heat exchanger design methods and the codes for predicting the thermodynamic and transport properties of the mixed hydrocarbon working fluids, can adequately predict the performance of the vaporizer as well as the condenser. In addition, specific tests are being conducted to evaluate the assumption of a close approach to integral condensation (integral condensation refers to the maintaining of thermal equilibrium between phases during condensation). Preparations are also in progress to examine the performance improvements that can be realized through the modification of the turbine inlet state points to achieve supersaturated vapor, turbine expansion processes. The verification that these supersaturated vapor expansions will not result in a degradation in the turbine efficiency, nor produce condensation which will result in damage to the turbine (if condensation does occur, the droplets will be too small to damage the turbine), will confirm that an additional 8% improvement in the net geofluid effectiveness can be achieved.

The preliminary work with the condenser in the vertical orientation was reported previously⁴.

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Facility Description

The Heat Cycle Research Facility (HCRF) is an experimental binary cycle facility used to investigate different concepts and/or components for generating electrical power from a geothermal resource. In the binary power cycle, the energy from the geothermal energy is transferred to a secondary working fluid, which is in turn expanded through a turbine driving an electrical generator. The HCRF components have the same function as those in a typical geothermal binary

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power plant, with the major differences being in size (the HCRF has a nominal power output of 40 kW) and that the HCRF components are designed to take advantage of the advanced plant concepts. This facility, which was formerly located at the Raft River geothermal site in Idaho, is now located at the DOE Geothermal Test Facility (GTF) at the East Mesa site in the Imperial Valley of southern California.

The HCRF in its current configuration is shown schematically in Figure 1. In this configuration the facility is operated as a supercritical cycle; that is, the working fluid vapor leaving the vaporizer is at a temperature and pressure higher than the fluid's critical point. As indicated in Figure 1, there are two supercritical heat exchangers, the preheater and the vapor generator, in which the energy from the geothermal fluid is used to vaporize the working fluid. (The geothermal fluid supplied to the facility is in the 310 to 325 °F temperature range.) The high pressure vapor leaving the vaporizer can then either be expanded through a turbine generating electrical power or through a bypass valve around the turbine. The low pressure vapor leaving either the expansion valve or the turbine is discharged into the condenser where the vapor is desuperheated and condensed by rejecting heat to the GTF cooling water system.

Fig. 1 Schematic of the Heat Cycle Research Facility

Heaters. The working fluid heaters are arranged in a hairpin configuration with the preheater on the bottom and the vapor generator on the top. The geofluid and working fluid have countercurrent flow paths through the units, with the working fluid entering on the bottom and flowing on the shell side of both units, and the geofluid entering on the top and flowing along the length of each unit inside the heat exchanger tubes. The preheater has tubes 28.21 feet long (tubesheet face-to-face) with an outside shell diameter of 5.56 inches. It contains 27, 1/2-inch OD, 19 fins/inch, low-fin tubes made of admiralty brass (has an outside-to-inside area ratio of 4.17). The vapor generator contains 39 of the same type tubes, with a 29.21 feet tube length and an outside shell diameter of 6.63 inches.

Condenser. The working fluid condenser is configured to provide for the in-tube condensation of the working fluid. The unit contains 419 internally-finned tubes, 1/2-inch OD and 18.54 feet long, made of 90/10 cupro-nickel (Noranda forge fin No. 6, with ten straight longitudinal fins inside each tube giving an inside-to-outside area ratio of 1.29). The working fluid vapor enters the upper end of the unit and is desuperheated and condensed as it flows through the condenser tubes. The liquid condensate leaving the tubes near the bottom of the unit is collected in the lower condenser head which serves as a reservoir. The cooling water to which heat is rejected circulates through the shell side of the unit.

Turbine-Generator. The turbine-generator assembly was designed and built by Barber-Nichols Engineering for the initial testing at the Raft River site in Idaho. It is an axial-flow impulse turbine which drives an induction motor/generator through a 6.135:1 gearbox. The generator's rated speed is 3600 rpm. Prior to initiating testing at the GTF, the turbine nozzle area was modified to accommodate the modified inlet conditions. The turbine/generator as presently configured, will nominally produce approximately 40 kW.

Experimental Approach

To accomplish the objective of developing the technology for advanced binary geothermal power plants, a number of Rankine-cycle experiments have been conducted for two different facility configurations using working fluids consisting of both pure and mixed hydrocarbons from both the propane, isopentane and the isobutane, hexane families, at nominally 0.5, and 10% of the heavier component (isopentane or hexane) by mass. The geofluid and cooling water flow rates were varied during the testing along with the working fluid flow rate, heater pressures, heater outlet temperatures, and superheat levels of the working fluid entering the condenser. These parameters were controlled to the extent possible, and similar test conditions were repeated for each of the working fluids tested. Tests were also conducted with a series of special propane, isopentane working fluids where the isopentane mass fraction was increased to levels approaching 50%. This particular series of tests were designed to provide further insight into the investigation of the departure from integral condensation exhibited by the condenser. In addition to these tests which were first conducted with the condenser in the vertical position, the effect of allowing turbine expansion processes to cross the saturation line and "pass through the two-phase region" was studied during several tests using the isobutane, hexane working fluids. This investigation of the effect the supersaturated vapor expansions on turbine performance was conducted with the vertical condenser orientation.

Following the completion of the testing with the vertical condenser, the HCRF was modified to provide for orienting the condenser at a near horizontal attitude (an inclination 10 degrees off the horizontal). Condenser tests conducted with the unit in the vertical position were

repeated with the near horizontal orientation to provide an indication of the relative change in performance for the different tube orientation. In addition to repeating a portion of the vertical tests, the condenser was temporarily modified to allow the cooling water direction to be changed from the original countercurrent flow path in the condenser to a cocurrent flow path. Modifications were also made during testing with the isobutane, hexane working fluid family to temporarily plug approximately half the condenser tubes. The intent of these modifications was to provide additional data on the condenser performance, beyond what the unit and the facility were designed for, in order to further evaluate the capabilities of the "state-of-the-technology" design methods, as well as to examine the effect of cocurrent flow paths and increased liquid loading in the condenser tubes on the approach to integral condensation.

Results

The primary emphasis of the recent efforts in the Heat Cycle Research Program has been in the analysis and evaluation of the heat exchanger data. The approach taken in this effort has been to first obtain the data for supercritical heating and vaporization in a finned tube heat exchanger as well as the condensation of hydrocarbon mixtures inside finned tubes. This data was then evaluated to determine how well a heater or condenser similar to those tested could be designed using standard design methods. To achieve these purposes, it was decided to use the computer codes developed by Heat Transfer Research, Inc. (HTRI) to rate the heat exchanger performance. These codes are commonly used for the design of heat exchangers and a direct comparison between the observed experimental performance and the calculated performance gives a measure of how well these codes would serve as design tools for this type of application. For the heaters, the HTRI computer code, ST-4 MOD 5.4, the shell-and-tube code with no phase change was used to evaluate performance. The condenser results were analyzed using the HTRI condenser code, CST-1 MOD 2.0. The working fluid properties used in the analysis of the data were determined by a computer program named "EXCST"⁵, developed by J. Ely at the National Bureau of Standards (NBS). This program which is based on an "Extended Corresponding States" theory, resulted in more consistent energy balances for the heaters and condenser than the other properties available to us.

Supercritical Testing with Condenser Vertical. The results of the component and cycle performance found with the supercritical cycle testing with the condenser in the vertical position are described in detail in a previous paper⁴. This test phase provide the data for identifying the procedures for evaluating the heater and condenser performance in addition to establishing the base line performance for each unit. The condenser performance at the vertical position provides the basis for comparison following subsequent modifications to the unit. Details of the analytical method are discussed in reference 4.

The heater results from this testing and evaluation indicate that the agreement between the calculated (using the HTRI codes) and the observed temperature distribution in the heater and vapor generator was quite good. Typical temperature profiles in the heater are shown in reference 4. In the "clean" condition, the HTRI code was underpredicted the heat transfer by about 20%, implying a conservatism, that if used for the design of a heater, the HTRI code would provide a heater with about 20% more area than what would actually be required if appropriate fouling factors are used.

Similarly the HTRI code did a very good job in predicting the condenser performance. If this design code was used in conjunction with the NBS property code and the method described previously⁴, the resulting condenser would produce a condensing (or bubble point) temperature which would be on the average, 0.4°F lower than the design condensing temperature. The results of the data evaluation at the vertical attitude are summarized in Figure 2 which shows the difference ratio of calculated to measured overall heat transfer coefficient for all fluids tested. Eighty percent of the points are within 20% of the measured values and 18 % of the remaining values are somewhat more conservative.

Fig. 2 Condenser Performance and the Predictive Method in the Vertical Orientation

Testing with the Near Horizontal Condenser. The testing with the condenser oriented in a near horizontal position (a 10 degree attitude), was completed early this year. Selected data sets have been reviewed and analyzed to determine the acceptability of the data and to assist in determining the final condenser position to be tested. In order to compare the condenser performance at two different positions (near horizontal and vertical), it is necessary to have two sets of data where everything is the same except for the orientation. Although test conditions were repeated as closely as possible for the two different positions, there were differences, particularly in the cooling water inlet temperatures over which the operators had no control. In order to account for these differences, the noted ability of the HTRI codes to predict the vertical condenser performance was

Fig. 3 Comparison of Condenser Performance in the Horizontal and Vertical Orientations

used to provide an indication of how the condenser would have performed if vertical and operating at the same conditions as during the near horizontal testing. The code was used to generate a correction to the vertical data, and provide a comparison on an "equal" basis between the two orientations. The results of this comparison is shown in Figure 3 as the difference in outlet temperatures for the two condenser positions for fluids from the propane, isopentane working fluid family. These results indicate that, the vertical condenser performance was slightly superior to that of the near horizontal performance, and that on the average the vertical condenser would provide an outlet temperature approximately 0.7°F lower than the horizontal unit.

In addition to comparing the relative performance of the two different attitudes, the HTRI code was also used to evaluate how well the predicted performance matched the observed performance. Initially the condenser was modeled similarly to that used during the vertical performance evaluation⁴ with the provision for the near horizontal tube inclination. The results of the evaluation using this model or procedure are shown in Figure 4 as model A. These results, based on a model which assumes the tube fins are 100% effective, indicate the HTRI code is not conservative at this condenser orientation. The next model used in the HTRI code assumed that the finned tubes were totally ineffective, i.e., the effective inside tube area was the same as that for a plain or bare walled tube. The results based on this assumption are shown in Figure 4 as model B. The HTRI code using this model provides a conservative prediction of performance, i.e., it indicates the calculated heat transfer coefficient is less than the observed value, or conversely, the calculated area is greater than the actual area. At this point, the effective ratio of the finned tube area to the plain tube area was varied to see if a single value would fit the data for each of the fluids considered. The results using this procedure for an area ratio of approximately 1.15 is shown in Figure 4 as method C. This method provides predicted performance which in general is within the desired 20% of observed performance.

Fig. 4 Condenser Performance and Predictive Methods in the Horizontal Orientation

This comparison of predicted near horizontal condenser performance and the observed condenser performance, suggests that the heat exchanger fins are not as effective in augmenting or enhancing the heat transfer area as it was in the vertical condenser position. It is important to note that the HTRI codes predict substantially improved performance at the near horizontal position and as noted earlier, the difference in the actual performance of the condenser between the horizontal and vertical positions was not that different. The reasons why the unit is not operating as the codes would predict, or why the code predictions appear to be unconservative, is not understood at this time. Additional work will be done in this area as the resources become available to the program.

Integral Condensation. As indicated previously, the projected improvements in the cycle performance from the advanced concepts is dependent on being able to approach integral condensation with the mixed-hydrocarbon working fluids. The effect of not achieving integral condensation, i.e., differential condensation, is shown as a band in Figure 5 because of the range of condensing pressures. If total differential condensation occurred, the fluid leaving the condenser would be at the condensing temperature of the pure

Fig. 5 Integral Condensation Tests

light component and, therefore, extremely subcooled with respect to the tabulated bubble point temperature (which should occur in integral condensation).

Data collected for both the vertical and horizontal orientations are shown in Figure 5 also. If there were no errors in the measured condenser outlet temperature, the working fluid chemical analysis or the thermodynamic properties none of the data would be negative. For integral condensation, the value would be zero. The data then indicates no evidence of differential condensation, only some errors in measurements or thermodynamic properties.

Supersaturated Turbine Expansions. The testing to date with the HCRF impulse turbine was conducted when the condenser was oriented in the vertical position. During this testing, a series of tests were conducted with an isobutane working fluid in which the turbine inlet state points were varied to provide data where supersaturated turbine expansions were allowed. The conditions for which these tests were run are summarized on the temperature-entropy plot in Figure 6. The

Fig. 6 Supersaturated Expansion Conditions Isobutane

effect of allowing these expansions on the turbine efficiency is shown in Figure 7. Two methods were used for defining the turbine efficiency; first using the measured inlet and

Fig. 7 Turbine Performance for Supersaturated Expansions, Isobutane

Fig. 8 Turbine Performance for Supersaturated Expansions, 95% Isobutane-5% Hexane

outlet pressures and temperatures to define an enthalpy change across the turbine, and second, using the measured power output and estimated parasitics to define the enthalpy change. In attempting to determine the effect of allowing these supersaturated expansions on the turbine efficiency, the magnitude of the efficiency was not as important as the efficiency trend that was noted as the expansion process proceeded into the region where a portion of the expansion was in the two-phase region. Estimates of the uncertainties in these calculated efficiencies suggest that the efficiency calculation using the power measurements would have the least amount of scatter (+1.4% as opposed to +5.6%). The results shown particularly for the efficiency as defined using the power measurement (the solid line) suggest that during this testing there was no measurable impact on the turbine efficiency when at least a portion of the turbine expansion was allowed to pass through the two phase region. Similar, though limited, testing was conducted with a 95% isobutane, 5% hexane working fluid. The results as shown in Figure 8 are similar to those obtained for the testing with the isobutane working fluid. Testing with these mixtures was limited by the available geofluid temperatures.

The turbine testing is discussed elsewhere⁶ in more detail. As indicated, the geofluid temperature limited the amount of testing that could be accomplished, particularly with the isobutane, hexane mixtures. The impulse turbine utilized for this testing, had a major gearbox failure before testing could be conducted with fluids from the propane, isopentane family. These fluids would have provided information on the effect of mixtures on the turbine performance; they are not candidate fluids for supersaturated expansions because they do not have retrograde dew point lines on a T-s plot (once isentropic expansion goes into the two-phase region, it does not come out).

Conclusions

The following conclusions are made as a result of the testing and analysis of the data made to date from the supercritical cycle experiments at the HCRF:

1. The HTRI code, ST-4, when used in conjunction with the NBS property code and accounting for property variation with temperature⁴, should give excellent results when used to design a supercritical heater/vaporizer; design will be 15% to 25% on the conservative side.
2. The HTRI code, CST-1, when used with the NBS property code and the method described in reference 4 to account for the finned surface, will provide excellent results for the design of a vertical condenser with in-tube condensing.
3. An in-tube, countercurrent condenser, with internally finned tubes will perform slightly better (approximately 0.7°F lower outlet temperature) in the vertical position than it will in the near horizontal position.
4. Questions remain with respect to applying the HTRI condenser code (CST) to the horizontal orientation in the design flow regime. Additional data will be analyzed at higher liquid loadings to determine whether the discrepancies are a matter of flow regime or something more basic.
5. No deviation from the assumption of an integral condensation process has been identified in the testing with the condenser at either of the tube orientations tested.
6. Supersaturated turbine expansion tests conducted thus far, have not shown any degradation in the turbine efficiency associated with expanding through the two-phase region.

References

1. O. J. Demuth, "Analysis of Mixed Hydrocarbon Binary Thermodynamic Cycles for Moderate Temperature Geothermal Resources", Proceedings of the 16th IECEC, pp 1316-1321 (August 1981).
2. O. J. Demuth and R. J. Kochan, "Analysis of Mixed Hydrocarbon Binary Thermodynamic Cycles for Moderate Temperature Geothermal Resources Using Regeneration Techniques", Proceedings of the 17th IECEC, pp1104-1109 (August 1982).
3. O. J. Demuth, "Preliminary Assessment of Condensation Behavior for Hydrocarbon Vapor Expansions which Cross the Saturation Line Near the Critical Point", Proceedings of the 18th IECEC, pp325-330 (August 1983).
4. C. J. Bliem, O. J. Demuth, G. L. Mines and W. D. Swank, "Vaporization at Supercritical Pressures and Counterflow Condensing of Pure and Mixed-Hydrocarbon Working Fluids for Geothermal Power Plants", Proceeding of the 21th IECEC, pp 61-65 (August 1986).
5. J. F. Ely, "Computer Code EXCST--Extended Corresponding States Theory," (Version 3.1), U. S. National Bureau of Standards, National Engineering Laboratory, Chemical Sciences Division, Boulder Colorado, June 29, 1983.
6. O. J. Demuth, C. J. Bliem, G. L. Mines and W. D. Swank, "Supercritical Binary Geothermal Cycle Experiments with Mixed-Hydrocarbon Working Fluids and a Vertical, In-Tube, Counterflow Condenser," Report EGG-EP-7076, Idaho National Engineering Laboratory, Idaho Falls, Idaho (December 1985).

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