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Effect of Mixed Working Fluid Composition on Binary Cycle Condenser Heat Transfer Coefficients

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Abstract:
The use of mixed working fluids in binary power plants can increase plant performance provided the heat exchangers are designed to take advantage of these fluids' non-isothermal phase changes. In the 1980's testing was conducted at DOE's Heat Cycle Research Facility (HCRF) where mixtures of different compositions were vaporized at supercritical pressures and then condensed. The focus of these efforts was on using the data collected to verify that Heat Transfer Research Incorporated (HTRI) codes were adequate for designing heat exchangers that could be used with mixtures. The HCRF investigations included a test series with mixtures of propane and 0% to 40% (molar) isopentane at condenser tube orientations of 10°, 60°, and 90° off the horizontal. Testing was performed over a range of working fluid and cooling fluid conditions. Though the condenser used in this testing was water cooled, the working fluid condensation occurred on the tube-side of the heat exchanger. This tube-side condensation is analogous to that in an air-cooled condenser. The sensitivity of the condensing coefficients to these composition, tube orientation and process conditions is being evaluated as the initial step in an assessment of the suitability of air-cooled condenser designs to take advantage of the performance gains possible with these fluids.

Key Words:
binary cycles, working fluid mixtures, condenser, heat transfer, heat transfer coefficients

Background:
As geothermal resources are developed that have increasing costs associated with finding and developing the geothermal resource, there will be increased incentive to build power plants that more effectively use the energy in the geothermal fluid that is produced. Developing more efficient plants requires minimizing the losses of the geothermal fluid's available energy in the different plant components and processes. Accomplishing this in binary power plants requires developing more efficient turbines and pumps and/or reducing the irreversibilities associated with the both the addition and rejection of heat. A simplistic method of reducing irreversibilities associated with a heat transfer processes is to increase surface area until approach temperatures (or pinch points) are approaching zero. There is a limit to which this approach can reduce the irreversibilities when phase changes occur, even with very small approach temperatures. There is also obliviously a limit to how large the heat exchangers can be before there is no economic benefit from increasing their size, though this limit is likely to vary from project to project. A commonly used and more cost effective method of reducing irreversibilities is to boil the working fluid at multiple pressures. Even further reductions in these losses can be achieved by vaporizing the working fluid at a supercritical pressure. Both of these approaches address the irreversibilities associated with the extraction of heat from the geothermal fluid; they tend to reduce the average temperature difference between the geothermal and working fluids, as well as allow more heat to be extracted from the geothermal fluid. Neither of these approaches are unlikely to increase the thermal efficiency for the power cycle; however they do increase the 2^{nd} law efficiency, which is an indicator of how well the cycle converts the energy in the geothermal fluid to power.

While these concepts have been successfully applied in existing plants to reduce the irreversibilities in the heat addition process, there are no similar approaches that reduce irreversibilities associated with the heat rejection process when a pure (single component) working fluid is used. Prior work by Demuth (1982) and Bliem (1991) indicated the use of non-azeotropic mixtures could provide increased binary plant performance. The performance benefit derived from these mixtures is due to their non-isothermal behavior during boiling and condensation, which can reduce the irreversibilities associated with each process. Demuth's work indicated that the use of mixtures could increase the performance of a supercritical cycle by 12% or more; this benefit is attributable to the condensation behavior of the mixed working fluids.

During the 1980's the Idaho National Laboratory (INL) investigated the use of these mixed working fluids in a small prototype binary plant, the Heat Cycle Research Facility (HCRF). This plant was capable of extracting up to ~1.5 x 10^6 btu/hr geothermal fluid, with maximum operating pressures of ~750 psia. These investigations examined the performance of the different cycle components using several working fluids in a supercritical cycle, as well as the ability to predict that component performance. The work focused on confirming that heat exchangers could be designed both to provide the non-isothermal behavior during phase changes, as well as to achieve the necessary counter-current flow paths. Major emphasis was placed on validating that the vapor and liquid phases would remain in equilibrium during the condensation process (integral condensation). A water-cooled condenser was used in this testing, with the mixtures condensed on the tube-side of the exchanger. In evaluating component performance with the mixtures, testing was performed with mixtures of isobutane and hexane, as well as propane and isopentane. To assess the effect of composition on condenser performance, a series of tests were conducted where the concentration of the isopentane in the propane-isopentane mixtures was varied from 0% to 40% (molar). In addition to varying mixture composition, testing was also performed with the condenser at 3 different orientations; 90° (vertical), 60°and 10° off the horizontal. A photo of the HCRF condenser at the 10° attitude is shown in Figure 1.

Figure 1. Heat Cycle Research Facility Condenser

These investigations (Demuth, 1985 and Bliem, 1989) confirmed that a water cooled condenser could be designed to achieve the desired condensation behavior with mixtures, i.e., both integral condensation and counter-current flow paths. In reporting results, emphasis was placed on the suitability of existing design tools, specifically the design codes developed by the Heat Transfer Research Incorporated (HTRI).

In 2009, INL received an ARRA award from DOE to investigate different methods of improving the performance of air-cooled binary plants that would likely be used in the near-term with EGS resources. Because of the postulated costs associated with developing and producing an EGS resource, one of the project tasks is to examine the suitability of existing air-cooled condenser designs for use with mixed working fluids. As part of this effort, data from the HCRF testing was recovered and is being used to assess whether the commercially available software that will be used to evaluate the air-cooled condenser design can adequately predict the in-tube condensation behavior observed during the prior testing. This paper is summarizes the overall heat transfer coefficients that have defined using the data taken during the HCRF testing.

Condenser Design:

A schematic of the condenser is shown in Figure 2. The condenser had a diameter of 18 inches, and contained 419 internally finned tubes (Noranda Forge-Fin No. 6) having an outside diameter of 0.5-inch. The longitudinal fins produced an inside to outside area ratio of ~1.43 (Carnavos, 1980). The tubes were 18.54 feet long (tube sheet to tube sheet), producing an outside surface area of 987.25 sq ft. Cooling water entered the shell side of the vessel ~6 inches below the upper tube sheet, and left ~6 inches above the lower tube sheet; shell-side baffles were located at 6-inch intervals. Working fluid vapor entered the upper head and condensed as it flowed downward through the tubes. Condensate was collected in bottom portion of the vessel below the lower tube sheet. This served as the hot well when testing with the condenser in the vertical position. For testing in the non-vertical positions, a hot well vessel was added to the plant as shown in Figure 1. This vessel provided the working fluid inventory needed for operation, the net positive suction head (NPSH) for the working fluid pump, and a means of assuring that there was no liquid accumulation in the condenser tubes.

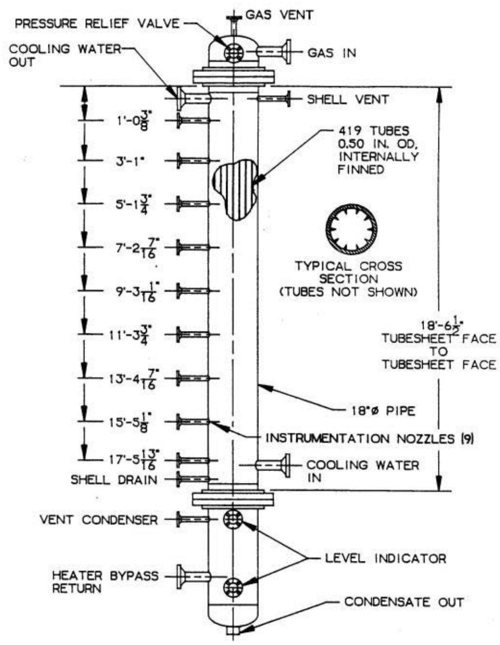

Figure 2. Schematic of the HCRF Condenser

The pressure and temperatures of the fluid streams entering and leaving the condenser were measured, as well as the fluid flow rates. Shell side cooling water temperatures were also measured at 9 intermediate locations, as shown in Figure 2. In addition to the process measurements, the composition of the working fluid was also measured for nearly all of the test conditions.

Results:

Again, the prior reporting of results by Demuth and Bliem focused primarily on the suitability of existing engineering tools both for characterizing the properties of the mixed fluids and for designing both the geothermal heat exchangers and the condenser. Though this work did indicate the design methods were adequate for sizing the heat exchangers, the reported results did not quantify the heat transfer coefficients or the effect of the mixture composition on those coefficients.

Because testing with the propane and isopentane mixtures was conducted with a larger variation in compositions, the focus of the current efforts has been on the evaluation of that data. Determining the overall heat transfer coefficients from this data is difficult because of uncertainties in process measurements, fluid chemistry, fluid properties, as well as fouling of heat exchange surfaces; these same uncertainties were encountered in the initial investigations. Pressure and temperature measurements at the outlet of the condenser along with measured composition and the fluid property method establish the amount of subcooling that occurred. In some instances, these measurements and the fluid properties indicate negative subcooling occurred, i.e., the outlet temperature is above the bubble point temperature indicated by the pressure measurement and the fluid property method. When this occurred prior to the addition of isopentane, the implication was that the fluid leaving the condenser was a vapor. To use this data, one must make assumptions relative to which measurement is incorrect – the fluid temperature, pressure, or chemistry (in all likelihood, all 3 are in error), as well as which property method to use. The determination of the heat transfer coefficient from the data is further complicated by the small internal approach temperatures (pinch points) that were achieved, in particular during operation with pure fluids. In some instances, the data indicates that negative pinch points were achieved, again implying issues with the process and fluid chemistry measurements and/or the property method.

In order to determine the heat transfer coefficient from the data, a protocol is being developed to assure that the data is evaluated on a consistent basis. The data will be evaluated with a single property method; at this time NIST RefProp (or a method that predicts similar properties to RefPop) is being used. If the data indicates negative subcooling, calculations are made assuming that each one of the 3 parameters (temperature, pressure, or chemistry) is incorrect. This provides a likely range of performance for the condenser, as well as an indication of sensitivity of the indicated performance to these measurements.

Initial testing was conducted with the condenser in the vertical position. This was followed by testing in the near-horizontal orientation (10° off the horizontal), which in turn was followed by testing at the near-vertical position (60° off the horizontal). The overall heat transfer coefficients (based on outer tube surface area) as a function of the composition is shown in Figure 3 at for each condenser orientation. Also shown in this figure is the overall heat transfer coefficient that was predicted based on the vertical test data using Aspen's Shell and Tube Exchanger (Tasc+) software. The data with no isopentane added (technical grade propane) indicates a superior condenser performance for the vertical orientation. It should be noted that because of the small approach temperatures (in some instances, <1°F) achieved with the technical grade propane, small errors in the temperature or pressure measurements can have significant impact in the magnitude of the heat transfer coefficients derived from the data. Any significant performance advantage for the vertical orientation is not as evident once the concentration of propane drops below 90% (molar). At these lower concentrations of propane (higher concentrations of isopentane), the condenser performance is similar for all the condenser orientations. We are re-visiting the data to assess whether the vertical condenser has a performance advantage at the higher concentrations of propane, or whether the apparent advantage is a result of the uncertainties in the process and chemistry measurements.

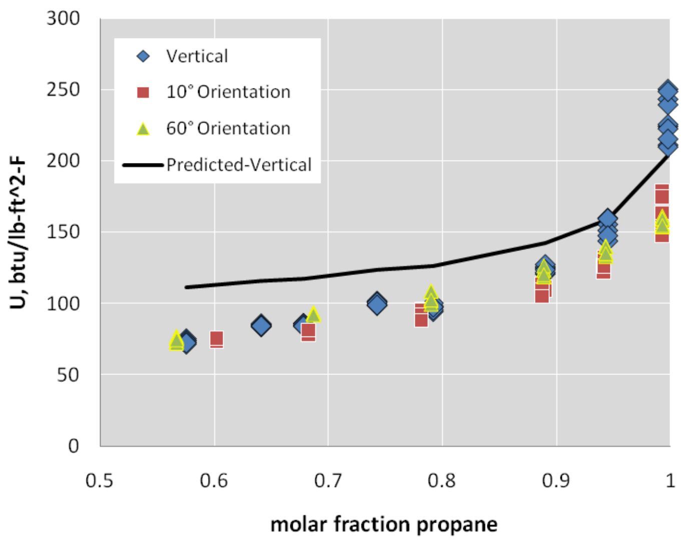

Figure 3. Overall Heat Transfer Coefficients for HCRF Condenser

It should be noted that only selected data sets from the vertical testing have been evaluated. The archived data is in paper or hard-copy form, and has largely yet to be put into an electronic format that facilitates its evaluation. Once more of the retrieved data has been evaluated, there may be more definitive trends in the effect of the condenser orientation on performance with the different mixture compositions. The data and logs are also being reviewed to determine whether there is anything to suggest that non-condensables may have been present during the testing. Samples of the vapor space in the hot well were periodically analyzed during testing to determining whether non-condensable gases were present. Archived gas chromatograph results are being reviewed to assess whether these measurements were made during this testing, and if so what levels of non-condensables were present. Archived data is also being examined to determine whether the calibration logs still exist that might help quantify instrument errors during certain periods of testing.

Though we are attempting to identify the possible explanations for the differences in performance at the vertical orientation, especially with pure propane, the emphasis of our work will shift to identifying the differences in performance between the near-vertical and near-horizontal condenser orientations. It is hoped that this data will provide further insight regarding the effect of the condenser attitude on performance, as well as an indication of impact of mixtures on condenser performance at a tube orientation that more closely approaches that found in existing air-cooled binary plants.

Conclusions:
The initial assessment of the testing performed at the Heat Cycle Research Facility with mixed working fluids indicates condenser performance was adversely impacted as the composition of the minor component (isopentane) increased. The magnitude of the impact is somewhat inconclusive because of uncertainty regarding the condenser performance with the single component fluid (propane). Cycle analysis suggests that for a 300°F geothermal fluid the highest cycle performance (2nd law efficiency) would be achieved using a mixture containing 10% to 15% isopentane (the remainder being propane). Test results suggest that for these compositions, the overall heat transfer coefficient for the vertical condenser would decrease by as much as ~45%, while the near-horizontal and near-vertical condenser

performance would drop by ~33% and 23%, respectively. The heat exchanger design tool predicts the condenser performance for these compositions would degrade by up to ~30%.

The HCRF test suggested that integral condensation was achieved, and that the condenser design produced the counter-current flow paths. Both of these are needed to attain the desired condensation behavior and resulting benefits from the mixed working fluids. Investigators hope to use this data to define an air-cooled condenser design that will also allow one to achieve the benefits from mixtures when evaporative cooling systems cannot be used.

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