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GEOTHERMAL HEAT CYCLE RESEARCH
SUPERCRITICAL CYCLE WITH COUNTERFLOW CONDENSER IN DIFFERENT ORIENTATIONS

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ABSTRACT

The Heat Cycle Research Program, which is 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. 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. The utilization of these concepts verified here will improve the net geofluid effectiveness (net watt hours plant output per pound of geofluid) about 20% over that of a conventional binary power plant. The major effect in this improvement is the ability to achieve integral, countercurrent condensation. Results are presented for the recent testing including those tests examining the performance of the countercurrent condenser at different tube inclinations and comparison with new design-base computer programs.

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 practical 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. (References 1, 2 and 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 use of integral, counterflow condensation is the major reason for this improvement. (Reference 4)

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 have been 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.

Many condensers are designed so that integral condensation and countercurrent flow are not achieved. Shell-side condensation in a horizontal orientation is a typical geometry for condensers. In this geometry, the liquid as it is condensed, falls away from the uncondensed vapor which sweeps on through the condenser. With the liquid stripped away from the vapor, the equilibrium between phases can not be maintained as required to produce integral condensation. In this case, the condensation more closely approaches differential condensation which exacts a performance penalty on the cycle. For this reason, it was decided to condense on the tube-side of this condenser and initially orient the tubes vertically in this experiment. Later tests at other orientations were to determine whether integral condensation was maintained.

The preliminary work with the condenser in the vertical orientation was reported previously. (Reference 5) The testing with the horizontal condenser was reported in Reference 6. Since that time, preliminary data is available for the inclined condenser (60 degrees to the horizontal). In addition, the Heat Transfer Research Inc. computer program which analyzes condensers has been improved to better model the internally augmented condenser tubes. It was felt appropriate at this time to evaluate this new computer tool and evaluate the condenser performance all three orientations.

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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 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, was then located at the DOE Geothermal Test Facility (GTF) at the East Mesa site in the Imperial Valley of southern California. The facility is presently being relocated at the B. C. McCabe Binary Plant site.

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 at the GTF has been 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 cooling water system.

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

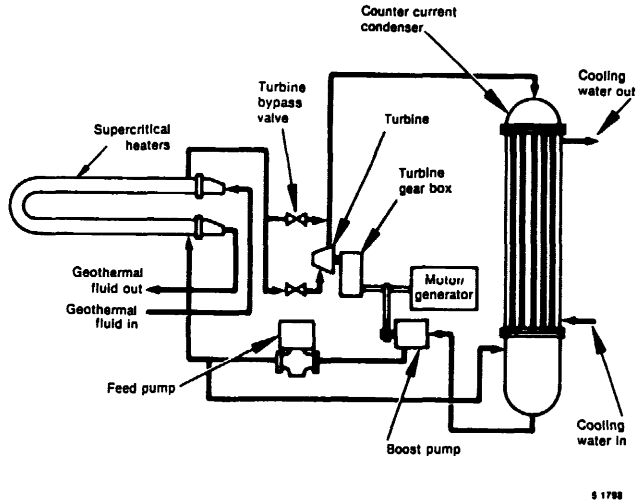

Figure 1 Schematic of the Heat Cycle Research Facility

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 to achieve integral condensation. 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 actual to nominal inside area ratio of 1.71). 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 served as a reservoir when the unit was in the vertical orientation. (In the other orientations, the condensate drained into a separate hotwell.) 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 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 mixtures of propane, isopentane working fluids were 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.

The last condenser modification was to tip the condenser to an inclination of 60 degrees to the horizontal. This was done to better approximate the intube heat transfer which would result in an A-frame air-cooled condenser. There was some evidence that plain tubes produced higher heat transfer coefficients when tipped slightly off vertical than in the vertical orientation. The tests run at this orientation were again to reproduce test conditions at the other orientations.

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 programs 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 programs would serve as design tools for this type of application. For the heaters, the HTRI computer program, ST-4 MOD 5.4, the shell-and-tube program with no phase change was used to evaluate performance. The condenser results were originally analyzed using the HTRI condenser program, CST-1 MOD 2.0. (See References 5 and 6.) The working fluid properties used in the analysis of the data were determined by a computer program named "EXCST" (Reference 7), 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.

The present condenser performance was analyzed using CST-2 MOD 0.0. This version of the code allowed a simpler modeling of the enhanced inside surface of the condenser tubes. With this version of the code, the enhanced surfaces are modeled by using appropriate heat transfer and pressure drop correlations to account for the effects of the augmented surfaces, i.e., experimentally determined single phase friction factor and "j" factor as functions of Reynolds Number. (Reference 8) The nominal tube diameter is used and a multiplier (safety factor) is used for the actual area enhancement of the fins (1.71). This allows the shell-side flow to be calculated correctly as well as the condensing fluid flow and heat transfer.

For the calculations reported in this paper, it was assumed that the condensed fluid left the condenser at a temperature 1 F lower than the bubble point temperature. Much of the previous work assumed this value to be 0.1 F. The earlier work indicated a more conservative calculation with respect to the measured values. For example the original calculation showed that approximately two-thirds of the data to be conservative. With the new assumption this is decreased to about one-third. The actual value is still to be determined, but these results are presented to give a method which will give accurate predictions for design if all the assumptions are carried in the calculation.

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 paper (Reference 5). 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 original analytical method are discussed in Reference 5.

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 5. In the "clean" condition, the HTRI code 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 using the old method did a good job in predicting the condenser performance. If this design code was used in conjunction with the NBS property code and the method described previously (Reference 5), 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 using the old method. The notation on all of the remaining figures to designate the composition of the working fluid used is as follows: A-100% Isobutane,
B-95% Isobutane/5% Hexane,
C-90% Isobutane/10% Hexane,
D-100% Propane,
E-95% Propane/5% Isopentane,
F-90% Propane/10% Isopentane, and
0-Higher percentages of isopentane
(percentages are by mass.) Seventy one percent of the points are within 20% of the measured

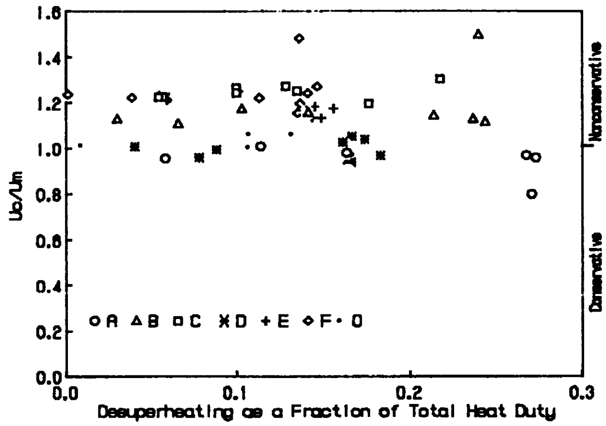

Figure 2 Condenser Performance and the Original Predictive Method in the Vertical Orientation

values. The majority of the data does lie on the unconservative side however.

Figures 3 and 4 show the results of using the new method. Figure 3 is comparable to Figure 2 using the old method. Note that the predictions are somewhat more conservative than for the old method. Ninety two percent of the data lies within 20% of the measured values (approximately tube, that multiplier could be adjusted. Initially, the value was set to the actual area ratio equally divided between the conservative and non conservative sides). This compares with 71% in the original method where approximately three fourths were on the unconservative side. Because the new method uses a multiplier on the augmented side to account for the area increase over a bare between finned and plain tube inside surface of 1.71. Figure 4 shows the adjusted multiplier to be multiplied by the actual area ratio of 1.71 for all of the data. Note that there appears to be a composition effect on the data with the pure

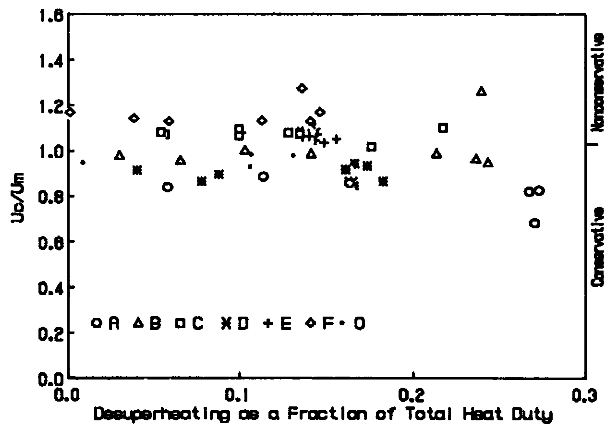

Figure 3 Condenser Performance and the New Predictive Method for the Vertical Orientation

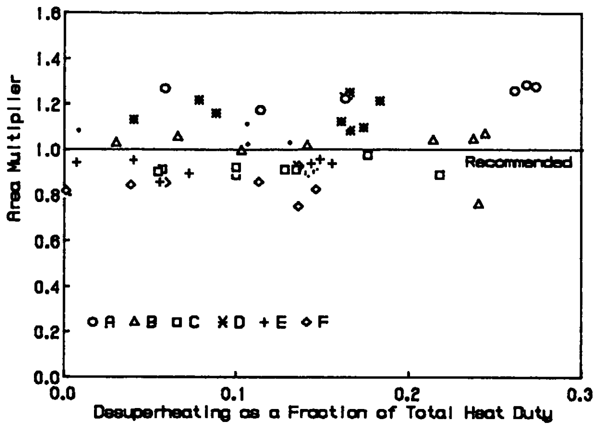

Figure 4 Corrective Multiplier for the New Method in the Vertical Orientation

components having a multiplier greater than one (around 1.15 to 1.2) and the mixture data having a multiplier on the area ratio less than one. This might be caused by the inability of the mixture to diffuse into the spaces between the fins and thereby render some of the area ineffective or might possibly be related to the method in which the data was reduced.

<u>Testing with the Near Horizontal Condenser</u>. The testing with the condenser oriented in a near horizontal position (a 10 degree attitude), was completed early in 1987. 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 much 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 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 are presented in Reference 6. These results indicated that in general, 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.

Figures 5 and 6 show results for the new method for the near horizontal orientation of the condenser in a format similar to Figures 3 and 4. For this orientation, the agreement with the HTRI calculation is much worse. For the majority of the data, the computer calculation (assuming horizontal tubes) is 50 to 80% higher than the experimentally measured values. If the HTRI program is used for this orientation, Figure 6 indicates that the area multiplier should be about 0.55 times the actual finned area. This is slightly less than the plain tube area for this tube. The fins appear to hinder the condensation heat transfer slightly over that of plain tubes. The reason for this is unclear at this time and will require further investigation. Until the situation is resolved, it is recommended that the HTRI program assuming horizontal tubes be used with the equivalent plain tube area used for the inside area. That is 1.0 would be used instead of 1.71 for this tube.

<u>Testing with the Condenser at a 60 Degree Orientation.</u> In the Summer of 1987, the condenser was tipped in such a manner that the axis of the

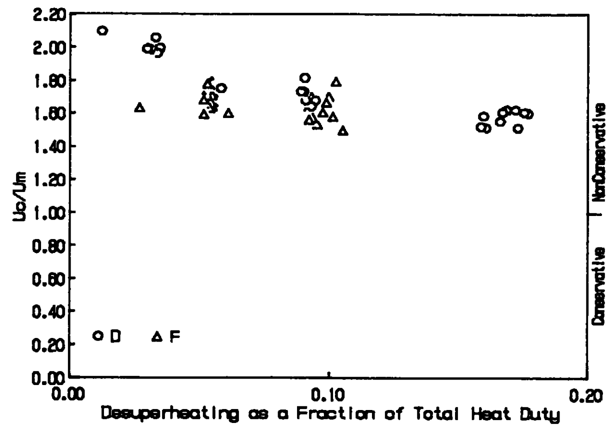

Figure 5 Condenser Performance and the New Predictive Method for the Near Horizontal Orientation

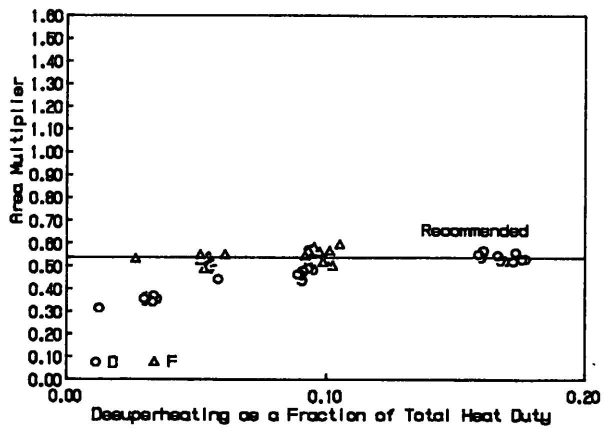

Figure 6 Corrective Multiplier for the New Method in the Near Horizontal Orientation

tubes made an angle of 60 degrees with the horizontal. Figures 7 and 8 show the initial results for the condenser in an orientation 60 degrees from the horizontal. The calculations assume that the condenser is vertical. Therefore, the deviation of Fignre 8 from Figure 4 expresses the difference between the performance at 60 degrees and the vertical orientation. This analysis approach was necessary because the HTRI computer program allows only vertical and near horizontal orientations.

Figure 7 indicates that the performance at the vertical orientation is about 20% higher than the performance at this orientation. Figure 8 indicates that a factor on the actual inside area of 0.8 along with the assumption that the calculations are carried out for the vertical orientation give good results.

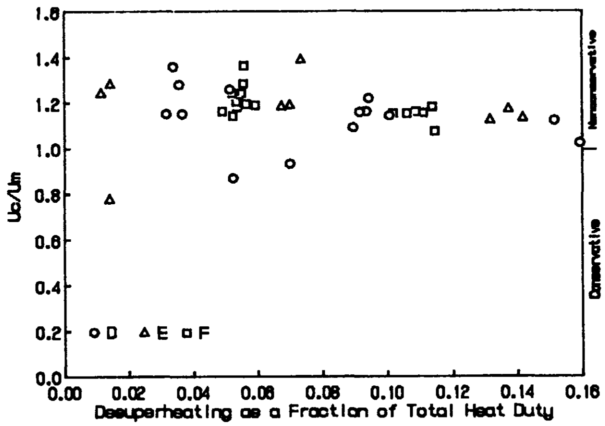

Figure 7. Condenser Performance and the New Predictive Method for the 60 Degree Inclined Orientation

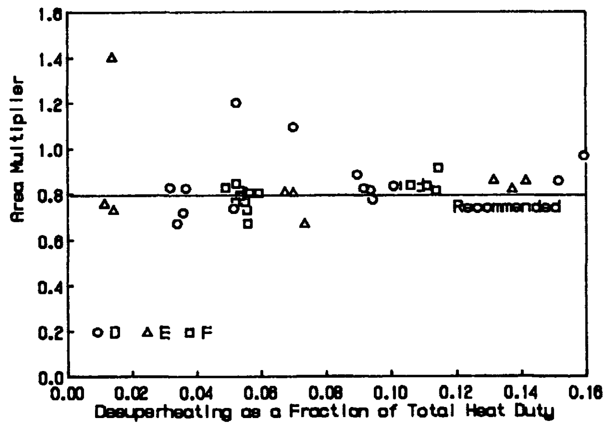

Figure 8 Corrective Multiplier for the New Method in the 60 Degree Orientation

<u>Integral Condensation.</u> 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 , <u>i.e.</u>, differential condensation, is shown as a band in Figure 9 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 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 60 degree and horizontal orientations are shown in Figure 9. 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.

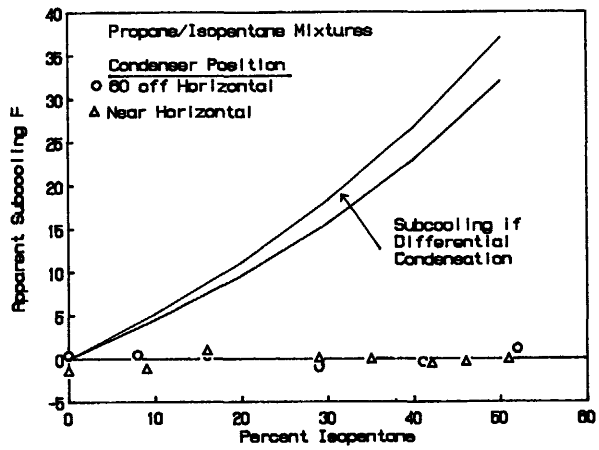

Figure 9 Integral Condensation Tests

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 computer program, ST-4, when used in conjunction with the NBS property code and accounting for property variation with temperature (See Reference 5.), should give excellent results when used to design a supercritical heater/vaporizer; design will be 15% to 25% on the conservative side.

2. The new HTRI computer program, CST-2, when used with the NBS property code and the method described here 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 (°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. At present, if an area correction factor of 0.55 is applied to the finned area and the computation assumes a horizontal orientation, the results are reproducible.

5. For a condenser tube tipped at an angle of 60 degrees with the horizontal, use the CST-2 program assuming a vertical orientation and correct the finned area by 0.8

6. 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.

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