IMPROVEMENTS IN BINARY CYCLE PERFORMANCE -- SUPERSATURATED TURBINE EXPANSIONS

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PROJECT BACKGROUND AND STATUS

The identified hydrothermal resources in the United States that are economically feasible for the commercial production of electrical power have been, or are being developed by the nation's geothermal industry. A large fraction of the nation's hydrothermal resources are only marginally feasible for the production of electrical power. To support the development of this energy resource, investigators in the INEL's Heat Cycle Research program have been working since the early 1980's to develop technologies that convert the energy in the hydrothermal resource into electrical power more efficiently. Lower power generation costs typically result from these more efficient cycles.

INEL has largely completed its efforts to identify concepts that produce significant performance improvements for binary power cycles. A cycle has been defined with a 20% improvement in the brine utilization (net power produced per unit mass of brine flow); the performance of this cycle approaches thermodynamic maximums. Field investigations at the Heat Cycle Research Facility (HCRF) validated the assumptions critical to achieving the performance improvement. They were also used to develop the technology base required to incorporate the advanced cycle concepts into the design of a commercial plant. The work on this advanced cycle has been completed.

One of the INEL analytical studies showed that brine utilization could be improved an additional 8% if the turbine inlet state points were modified to allow turbine expansions that "passed through" the two-phase region. The turbines in conventional binary plants are operated with sufficient superheat at the turbine inlet that the entire expansion process remains completely "dry". This operating constraint is applied to the turbine because of concern that any condensation forming during the expansion process would adversely affect the turbine's performance and/or damage (by erosion) its internal components. The INEL study suggested that condensation would not occur, and that if condensate droplets did form, they would be small and tend not to grow to a size that would cause damage or affect performance.

Before the closure of the HCRF in 1994, investigations were conducted at that facility to examine the condensation behavior of these metastable, supersaturated expansions and to determine their effect on turbine performance. The remaining issues to be resolved are currently being investigated at a binary power plant operated by Mammoth Pacific Limited Partnership. The investigations at the Mammoth facility are examining the impact of these expansions on a commercial turbine over an extended period. At the conclusion of this extended test, turbine operating parameters will be defined that minimize the potential for damage, while allowing a binary plant operator to maximize the amount of power produced from a given flow of brine.

PROJECT OBJECTIVES

The objective of the Heat Cycle Research program is to reduce the cost of generating electrical power from marginal temperature hydrothermal resources. This is being accomplished by developing binary power cycle technologies that allow the cycle performance to approach thermodynamic maximums. The objective of the project investigation of metastable, supersaturated turbine expansions is to define the turbine operating conditions that increase the amount of power produced from a given amount of brine without damaging the turbine or affecting its performance.

Technical Objectives

- Define the conditions producing condensate formation and the operating parameters that will support a supersaturated vapor during the turbine expansion process.
- Determine the degree of supersaturation and/or moisture that can be tolerated during the expansion process without degrading turbine efficiency.
- Identify the effects of these metastable expansions on internal turbine components (rotor and nozzle/vane surfaces), and on turbine performance over an extended period of operation.

Expected Outcomes

- Metastable, supersaturated vapor expansions can proceed without adversely effecting turbine performance.
- Erosion effects of the supersaturated vapor are not significant up to the point of condensate formation.
- A turbine can operate for short periods of time with "wet" expansions without damaging its internal components. (These "wet" expansions would typically occur during a plant conditions when significant levels of liquid would be present in the working fluid as it is expanded through the turbine.)

Expected Outcomes (continued)

- The power production will be increased or the brine usage decreased (while maintaining the same power output) by reducing the conservatism in the amount of superheat maintained at a binary cycle turbine inlet.

- A mode of operation will be defined that could improve the brine utilization by up to 10%.

- The cost of electricity is projected to decrease by 3% to 5% for an increase of 8% to 10% in the brine utilization.

APPROACH

The investigation of the condensation behavior of the metastable, supersaturated vapor expansions were initially conducted at the HCRF. A converging-diverging nozzle was used to simulate the expansion in a turbine, and a droplet detection system was used to detect the presence of condensation in the expansion process. These simulated expansions provided investigators with information on the conditions producing condensation, the size of the droplets that formed, and the conditions under which the formed drops evaporated as the expansion continued. From the data generated, the degree of supersaturation attained before condensate forms can be identified.

Field investigations were conducted at the HCRF with both an impulse turbine and a reaction turbine; both turbines were prototype size. These tests determined the degree of supersaturation or moisture level sustained in the turbine expansion before the efficiency is adversely affected. During these investigations, the turbine operating conditions were closely monitored and controlled. At fixed operating pressures, the turbine inlet temperature was varied to control the degree to which the turbine expansion process was allowed to enter the two phase region. The turbines were operated at inlet conditions producing (as defined by the nozzle tests) "dry" expansions, supersaturated expansions, and "wet" expansions. The turbine performance was monitored at each test condition to define the point at which a degradation in performance occurred. This point was correlated with the nozzle tests to determine the degree of supersaturation or moisture level present in the turbine expansion. This process was repeated at different inlet and exhaust pressures, as well as with different working fluids.

To determine the long-term effects of these expansions on a turbine's performance and internal components, the investigations are continuing at a commercial binary power plant. This plant will be operated over an extended operating period with its turbine having a controlled degree of supersaturation in the expansion process.

Before starting an extended period of operation, the condition of the internal turbine components is to be documented, and the "baseline" performance of the turbine and plant established for a "dry" expansion process. The turbine inlet conditions will then be modified to provide the desired degree of supersaturation, and maintained for the duration of the test. The turbine performance will be monitored over the test period to determine whether efficiency degrades with time. At the conclusion of the extended operation, the components internal to the turbine will be removed and examined for any abnormal wear or erosion.

At each phase of the metastable, supersaturated turbine expansion investigations, industry review and comment is solicited from turbine manufacturers, plant operators, and engineering-design firms active in the geothermal industry. With increased interest, these entities loan or donate materials and services to the investigation (in-kind contributions). The ultimate objective is to generate sufficient industrial interest to have the concept incorporated into the operation of a turbine in a commercial plant.

RESEARCH RESULTS

The initial investigations of the condensation behavior of the metastable, supersaturated vapor expansions and their effect on turbine performance were conducted at the HCRF prior to its closure at the end of 1994. Tests with an expansion nozzle and a droplet detection system confirmed that a supersaturated vapor was achieved during the simulated turbine expansion of an isobutane working fluid. It was estimated that the brine utilization in a commercial plant would increase by up to 10% at the maximum level of supersaturation achieved in these tests. Tests conducted with an axial-flow, impulse turbine and a radial-inflow reaction turbine verified there was no adverse impact on the performance at the levels of supersaturation achieved in the nozzle tests; the effects of these expansions on turbine performance are shown in Figure 1 for the axial-flow, impulse turbine and Figure 2 for the radial-inflow, reaction turbine.

The objective of these tests was to determine the impact of the supersaturated expansions on the performance of each type of turbine; it was not to compare the performance of the two types of turbines relative to each other. (There are a number of probable causes for the radial-inflow turbine efficiency being low; a similar type of turbine operating and tested at Mammoth Pacific has efficiencies greater than 85%.) The performance of the turbines did not begin to degrade until their expansions (as indicated by the nozzle tests) would have produced significant levels of condensate formation. The impulse turbine efficiency was not affected until the vapor leaving the turbine was "wet", i.e., the actual exhaust condition was within the two-phase region. The radial-inflow reaction turbine did not tolerate the same moisture level before its performance was affected; its efficiency began to degrade once the isentropic exhaust condition was within the two-phase region. The "wet" expansions data shown in Figures 1 and 2 correspond to an isentropic exhaust condition which on the dew point curve, or just outside the two-phase region. Similar results were obtained in both turbines for an isobutane working fluid and a 95% isobutane, 5% hexane mixture (see Figures 1 and 2).

During the testing at the HCRF, each turbine was operated for a few hundred hours. Although there did not appear to be any unusual wear on the impulse turbine components, there was erosion damage to the stationary internal surfaces (including the nozzles) in the reaction turbine. Discussions with the turbine manufacturer, an engineering firm, and a plant operator using a similar turbine suggested the erosion damage was due to small particulate entrained in the working fluid vapor; the particulate was residue from the plant construction activities. A similar phenomenon had occurred at commercial plants; it was resolved by installing filters and/or separators upstream of the turbine.

While the results of the HCRF investigations showed the supersaturated expansions did not adversely affect performance, they did not resolve the question of the long-term impact of these types of expansions on the turbine. To address this issue, an agreement was reached in 1995 with Mammoth Pacific Limited Partnership to continue these investigations at one of it's plants (MP-100) near Mammoth Lakes CA. The radial-inflow, reaction turbine at MP-100 will be operated at inlet conditions producing the supersaturated vapor expansions over an extended period to determine the long-term impact of these types of expansions. The turbine manufacturer and the engineering firm that designed the plant are involved in defining the conditions for the extended operation, and will participate in evaluation of the data generated and reporting the results.

The initial phase of this effort required examining the feasibility of operating the MP-100 plant at turbine inlet conditions producing the supersaturated vapor expansions. This plant was designed for the commercial production of electrical power; it was not designed with the same operation flexibility as the HCRF. The initial investigations at MP-100 indicated that it would not be feasible to operate the turbine at supercritical inlet pressures because of the associated decrease in electrical power production. It would be possible to operate with subcritical inlet pressures and inlet entropies comparable to those producing condensate formation in the nozzle tests at the HCRF. To achieve these conditions, it would be necessary to operate with ~1°F of superheat at the turbine inlet. This level of superheat is substantially less than that used during the normal operation of the MP-100 turbine (~8°F). The initial investigations at MP-100 suggested that this could be accomplished, and that the turbine could tolerate short periods of operation with "wet" expansions.

Based on the feasibility tests, the flow and inlet pressure conditions selected for the extended test were similar to those for which the turbine was originally designed. Mammoth initiated the procurement of a new turbine rotor and nozzle set based on the original design for the extended investigation. To minimize the risk to Mammoth, as well as to assure the condition of the components and establish their pre-test condition, the project will purchased these components from Mammoth. They will be installed once received during the first quarter of FY-1996.

FUTURE PLANS

During the first quarter of FY-1996, Mammoth Pacific will receive the new turbine rotor and nozzle set. Once the pre-test condition of these components is documented, Mammoth will install them in the MP-100 turbine. After establishing the performance of the turbine with these components using completely "dry" turbine expansions, the inlet conditions will be modified to provide the desired degree of supersaturation in the expansions. This will become the "normal" operating point for MP-100 for approximately 6 months. At the end of this period, a mutual decision will be made whether to continue the investigation for an additional 6 months (or longer). At the conclusion of the extended test, the turbine rotor and nozzle set will be removed and their post-test condition documented. The results of the investigation will be reported. If the results of the investigation are favorable, it is expected that Mammoth Pacific will make similar modifications to the inlet conditions for the turbines at one or more of its other binary plants in the Mammoth area. The successful completion of this activity will result in the transfer of the technology to industry, and its initial commercial application.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Barber-Nichols, Inc.	Turbine manufacturer and engineering firm: assisted with field testing of the impulse and reaction turbines at the HCRF and subsequent data evaluation; provided (at no cost) equipment for the testing of the impulse turbine.
Mission Energy	Binary plant operator: provided review and comment on project investigations conducted at the HCRF.
Rotoflow Corp., Inc.	Turbine manufacturer: provided (at no cost) the rotor and nozzles for testing the reaction turbine at the HCRF; provided review and comment on HCRF studies; assisted the project in soliciting interest from geothermal plant operators for the extended test; providing turbine rotor and nozzle set (at a discount) for the extended test.
CE Holt Co.	Engineering firm: provided review and comment on HCRF studies; assisted in soliciting interest from geothermal plant operators for the extended test; providing engineering services, including data evaluation, to Mammoth Pacific during the extended operation test.
Mammoth Pacific LP	Binary plant operator: making its MP-100 plant available for the extended operation with the supersaturated expansions; providing operational and maintenance personnel for activity at no cost; foregoing any lost revenues during shutdowns and testing.

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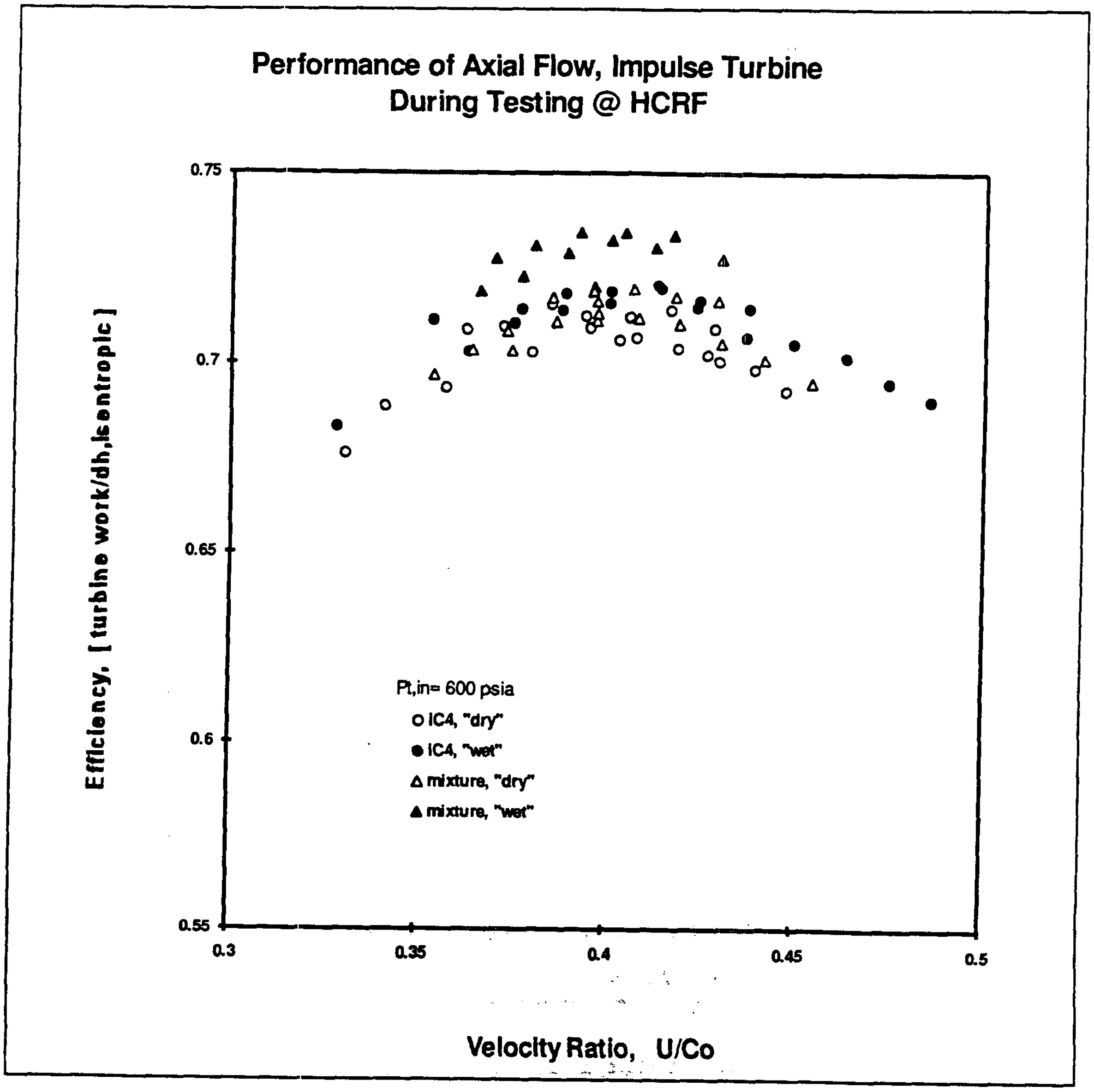

Figure 1. Performance of Axial Flow, Impulse Turbine During Testing @ HCRF

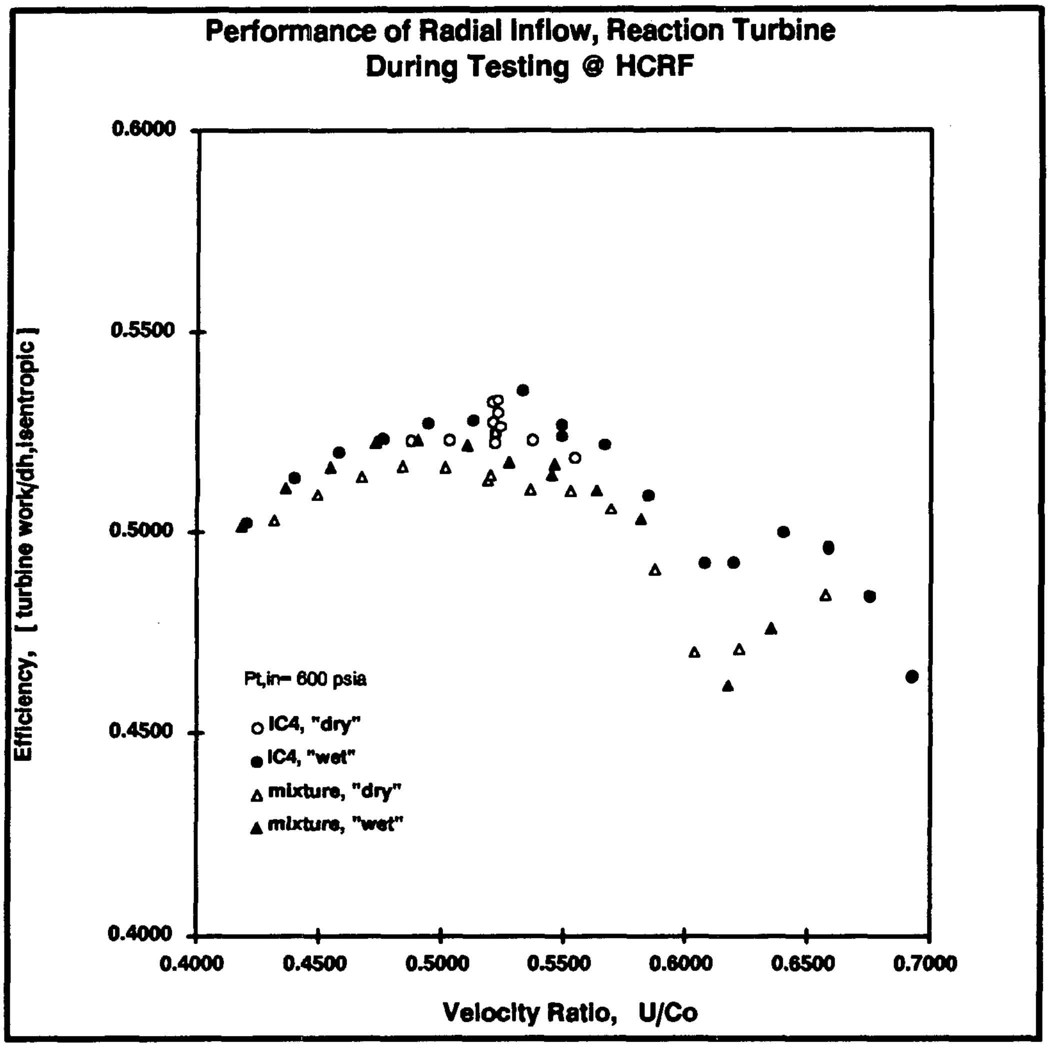

Figure 2. Performance of Radial Inflow, Reaction Turbine During Testing @ HCRF