IMPROVEMENTS IN BINARY CYCLE PERFORMANCE: SUPERSATURATED TURBINE EXPANSIONS

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binary power cycles, turbines, supersaturated expansions, metastable turbine expansions

PROJECT BACKGROUND AND STATUS

Since the early 1980's the INEL's Heat Cycle Research project has been developing binary cycle technologies that support the development of the nation's hydrothermal resources considered marginally feasible for electrical power production. The technologies developed allow the energy in the hydrothermal resource to be more efficiently converted into electrical power. The more efficient cycle typically results in lower power generation costs.

An INEL study showed that the brine utilization (net power produced per unit mass flow of brine) of a supercritical cycle increased by $\sim 8\%$ after modifying the turbine inlet state points to allow expansions in the turbine to "pass through" the two-phase region. If brought to equilibrium conditions, liquid condensate would form in the vapor during these expansions. These types of expansions are avoided in commercial binary plants because this condensate could cause erosion damage to the turbine and adversely affect performance. In the commercial plant, sufficient superheat is added to the working fluid to assure the expansion through the turbine remains completely "dry". The study suggested that the condensate would not necessarily form. The turbine expansion is a metastable process. Depending upon the extent to which the expansion enters the two-phase region, a supersaturated vapor is supported. If condensate forms, the droplets would initially be quite small and tend to evaporate as the expansion process proceeds.

Prior to the closure of the Heat Cycle Research Facility (HCRF), the condensation behavior of these metastable expansions was investigated. Investigations were also conducted at the HCRF that examined the impact of these expansions on the performance of two prototype-sized turbines. The investigations showed a supersaturated vapor was supported in simulated turbine expansions. The supersaturated expansions did not affect the performance of the turbines until the vapor exhausted the turbine within the two-phase region. The turbine investigations were limited in duration and did not adequately resolve whether these expansions would adversely affect performance and/or damage the turbine over an extended period of operation.

An agreement was reached with Mammoth Pacific Limited Partnership (MPLP) to operate one of MPLP's binary plant turbines with the metastable, supersaturated expansions over a period of up to one year. (MPLP's facilities are located near Mammoth Lakes, CA.) During this period the performance of the turbine is monitored to determine whether there is any degradation in efficiency attributable to operation with these expansions. In November of 1995 a new turbine rotor and set of vanes were installed in MPLP's MP1-100 turbine and operation with the metastable expansions initiated. Excluding periods of abnormal operation, the MP1-100 turbine continues to operate with these expansions.

PROJECT OBJECTIVES

The objective of the Heat Cycle Research Project is to develop technologies that reduce the cost of generating electricity from those hydrothermal resources considered marginally feasible for economic development. The investigation of the impact of metastable, supersaturated expansions is to define a mode of operation that will increase the amount of power that can be produced from a given brine flow. This is to be accomplished without damaging the turbine or adversely affecting performance.

Technical Objectives

- Define the turbine inlet conditions supporting a supersaturated vapor during the turbine expansion process. Identify those conditions resulting in condensate formation.
- Determine the degree of supersaturation or moisture content tolerated in the turbine expansion without a degradation in turbine efficiency.
- Demonstrate the metastable, supersaturated expansions do not adversely affect turbine performance or damage its components.
- Identify modifications necessary to maximize the performance gain when utilizing these expansions in an existing turbine.
- Determine whether the metastable, supersaturated expansions can be utilized in turbines having sub-critical inlet pressures.
- Develop control methods allowing these expansions to be utilized and provide assurance that this mode of operation will not damage the turbine.

Expected Outcomes

- The metastable expansion of an isobutane working fluid through the two-phase region supports a supersaturated vapor.
- The metastable, supersaturated expansions proceed without adversely affecting turbine performance or damaging the turbine.
- The metastable expansions can be utilized to improve the performance of an existing binary plant (not designed for operation with these expansions).
- Metastable expansions can be utilized in binary power cycles with sub-critical turbine inlet pressures and minimal superheat at the inlet.
- The brine utilization of a binary plant increases by up to ~8% when using the metastable turbine expansions.

APPROACH

Analytical studies identified a performance gain that could be achieved if the metastable, supersaturated turbine expansions did not adversely affect turbine performance or damage the turbine. In order to confirm that the projected performance improvement could be realized, field investigations were initiated to validate the assumptions used and conclusions reached in the analytical studies. The first two phases of the field investigations were conducted at the HCRF. In the first phase, investigators examined the condensation behavior of the metastable expansions using a converging-diverging nozzle to simulate isentropic turbine expansions. These investigations identified the conditions that produced the onset of condensation, established where in the expansion process condensate first started forming, and determined the conditions under which the condensate evaporated as the expansion proceeded.

In the next phase, the project investigated the effect of these expansions on the performance of an axial flow, impulse turbine and a radial-inflow, reaction turbine (both prototype-sized). During this effort, two turbine manufacturers were involved in the project investigation; Barber-Nichols Engineering and Rotoflow Corp. The turbine tests identified the inlet conditions in both turbines that produced a degradation in performance (efficiency). These inlet conditions were then correlated with the nozzle tests to identify the degree of supersaturation or moisture present in an isentropic turbine expansion. Tests were conducted at supercritical inlet pressures with both pure (isobutane) and mixed (isobutane, hexane) working fluids.

The turbine tests at the HCRF were not of sufficient duration to determine how these expansions would affect the turbine after an extended period of operation. For the next phase of these investigations, an agreement was reached with a commercial binary power plant operator to operate an existing turbine with the metastable, supersaturated expansions for an extended period. Mammoth Pacific Limited Partnership (MPLP), the plant operator, agreed to operate its MP1-100 turbine with the metastable expansions for a period of six months or more.

Prior to initiating operation with the metastable expansions, the project purchased a new turbine rotor and set of vanes that MPLP installed in the turbine. The pre-test condition of the components was documented (photographs) and the performance of the turbine established at normal operating conditions. The turbine inlet conditions were then adjusted to provide the desired degree of supersaturation. Except for abnormal periods of operation, these conditions are maintained for the duration of the test. The turbine performance is monitored to identify any degradation in efficiency. At the conclusion of the test, the turbine components will be examined for any unusual wear or erosion. If damage due to the metastable expansions is suspected, the rotor and vanes will be removed and a more detailed examination made.

The investigation at MP1-100 will assist the project in establishing a control scheme for operating with the metastable expansions that will minimize the potential for damage to the turbine. The investigation will also identify the problems associated with attempting to incorporate these expansions into an existing plant not designed for this mode of operation.

At each phase of the investigations, the project has solicited industry comment on the results of the investigations to that point and the plans for the next phase of the investigation. As the results of the investigations have shown the potential benefit of operating with these expansions, turbine manufacturers, plant operators, and engineering-design firms have provided materials and services (in-kind contributions). The final phase of this investigation will be the incorporation of these metastable expansions in the operation of a commercial power plant. During this phase, the project will provide technical support in exchange for operating data.

RESEARCH RESULTS

The first two phases of the investigation of the impact of operating with metastable, supersaturated turbine expansions on turbine performance were completed prior to the closure of the HCRF. The investigation of the condensation behavior of these expansions with the converging-diverging nozzle indicated that a supersaturated vapor was supported until an equilibrium moisture level of 5% to 6% was reached. At the onset of condensate formation, the droplets that formed evaporated as the expansion proceeded. The range of inlet conditions over which this occurred was relatively small, corresponding to ~1% increase in the equilibrium moisture level.

The HCRF testing with the axial-flow, impulse and radial-inflow, reaction turbines indicated the performance was not adversely impacted at conditions producing condensate formation in the nozzle. The impulse turbine efficiency was not affected until the conditions exhausting the turbine were inside the two-phase region. This corresponded to a maximum equilibrium moisture level of ~25%. The reaction turbine efficiency was affected when the isentropic exhaust conditions were inside the two-phase region. The maximum equilibrium moisture level that was obtained in the reaction turbine before its performance degraded was ~15%. Neither turbine's components appeared to be damaged by operating with the metastable expansions, however the period of operation with these expansions was less than 200 hours for each turbine.

An agreement was subsequently reached with MPLP that would allow one of its binary plant turbines to be operated with the metastable expansions for a period of six months or more. In November 1995, a new turbine rotor and set of vanes were installed in MPLP's MP1-100 facility turbine. Once operation of the facility resumed, the turbine inlet conditions were adjusted to allow the isobutane vapor to pass through the two-phase region producing the desired metastable expansions. The modified and typical turbine inlet conditions are depicted on the temperature-entropy (T-s) plot in Figure 1. The dashed constant entropy lines depict an ideal expansion process in the turbine (the isobutane expansion through the turbine nozzles approaches this ideal process). As indicated, for the extended investigation the turbine operates with minimal superheat at sub-critical inlet pressures.

The MP1-100 turbine operated with the metastable expansions through May 1996 without any measured degradation in efficiency. After reviewing the turbine and plant performance, MPLP and INEL mutually agreed to continue the investigation. With the consent of MPLP, INEL investigators have periodically increased the degree of supersaturation (extent to which the expansions enter the two-phase region) in the expansions. The nominal equilibrium moisture content in the metastable expansions during the investigation was ~ 3% to 5%, although during a portion of the operation moisture contents of up to ~7% were present. (The level of supersaturation is limited by the operation with sub-critical inlet pressures.)

The efficiency of the MP1-100 turbine while operating with the metastable expansions for the period from November 1995 to October 1996 is shown in Figure 2. (The efficiencies shown are calculated using the generator output to determine the actual turbine work.) During the period between March and May 1996, the data acquisition system at the MP1 facilities was not operating, and data was not available. (The MP1-100 facility continued to operate with the metastable expansions, using readings from non-recording indicators and gauges to monitor the turbine operation.) When data was available in May, the turbine efficiencies were slightly lower and there was more variation in the values. The scatter, or variation in the turbine efficiencies, is due in part to the fluctuation in the ambient air temperature (and turbine exhaust pressure). In Figure 3, the efficiency trend with the ambient air temperature is shown.

The data depicted in Figure 3 shows that at a given ambient air temperature, the efficiency of the MP1-100 turbine remained essentially constant after just less than one year of operation with the metastable expansions. Minimal difficulties were encountered in operating the plant despite superheat levels of less than 1 °F at the turbine inlet.

Mammoth's MP1 facility consists of two identical, and independently operated binary power plants. During this investigation, the MP1-200 plant was operated in a typical mode, with the vapor superheated sufficiently before entering the turbine to assure the expansion remains completely outside the two phase region. While operating with the metastable expansions, the MP1-100 unit's power output was consistently 10% to 25% greater than the MP1-200 plant when operating at equivalent brine inlet conditions.

FUTURE PLANS

In November 1996, one year of operation with the metastable expansions will be reached. A report of the results will be prepared summarizing the results of the first year of operation. At the next shutdown of the MP1-100 unit, the turbine rotor and vanes will be examined to determine whether any unusual wear has occurred to those surfaces exposed to the expanding metastable vapor. Given the success of this investigation, INEL researchers will contact the operators of other candidate binary facilities to solicit interest in operating these facilities with the metastable turbine expansions.

The project will also begin to assess the feasibility of modifying a turbine to achieve the maximum benefit of using the metastable expansions in an existing plant.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Type and Extent of Interest
Barber-Nichols, Inc.	Turbine manufacturer and engineering firm: assisted with the field testing of the impulse and reaction turbines at the HCRF and the 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.

Organization	Type and Extent of Interest
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 investigations; assisted the project in soliciting interest from geothermal plant operators for the extended test; providing turbine rotor and nozzle set (at discount) for the extended test.
CE Holt Co.	Engineering firm: provided review and comment on HCRF investigations; assisted the project 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: made 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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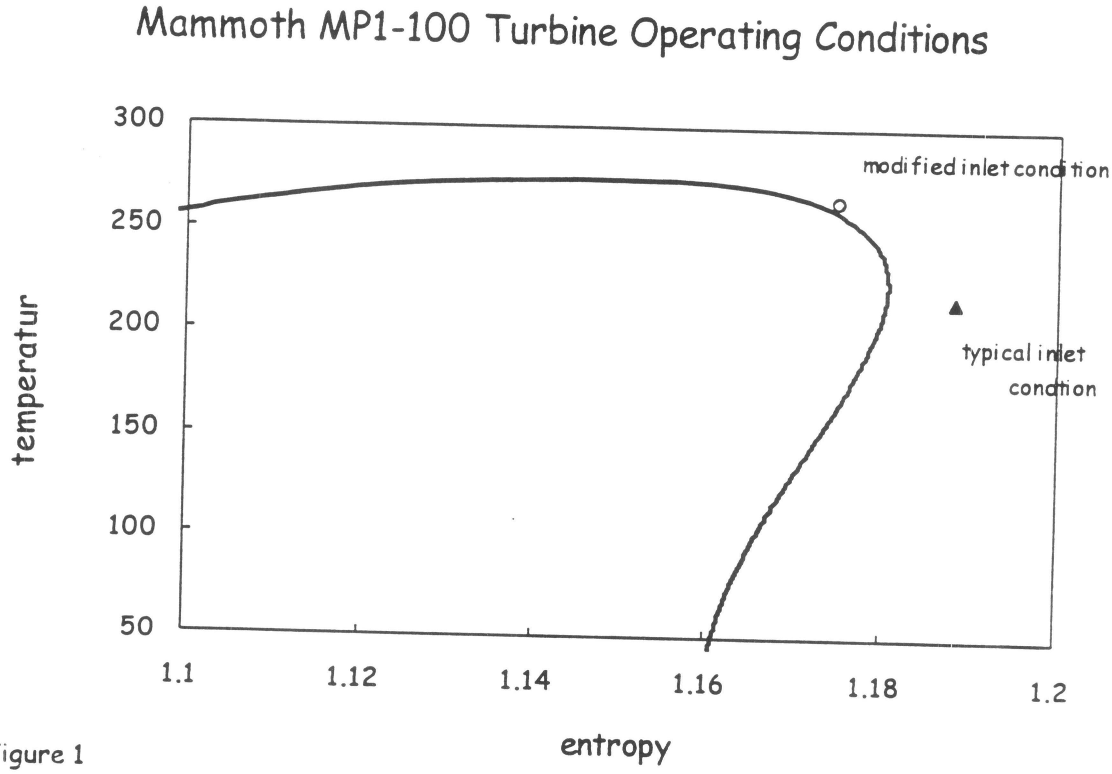

Figure 1

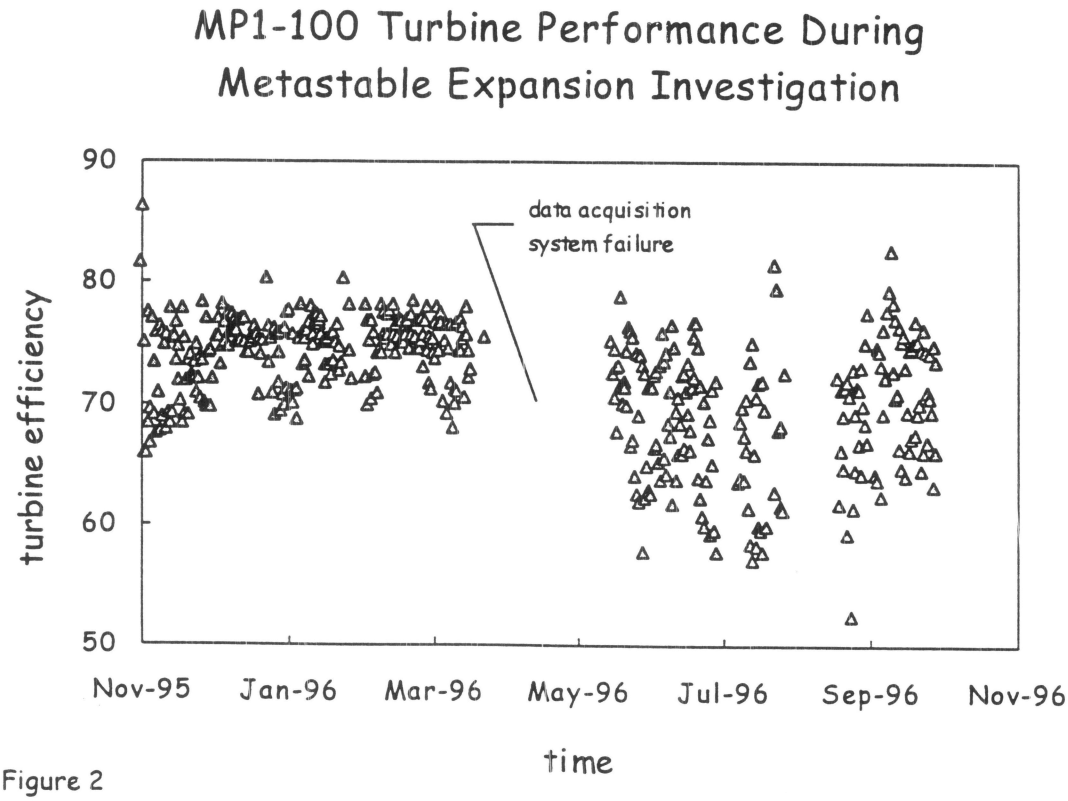

Figure 2

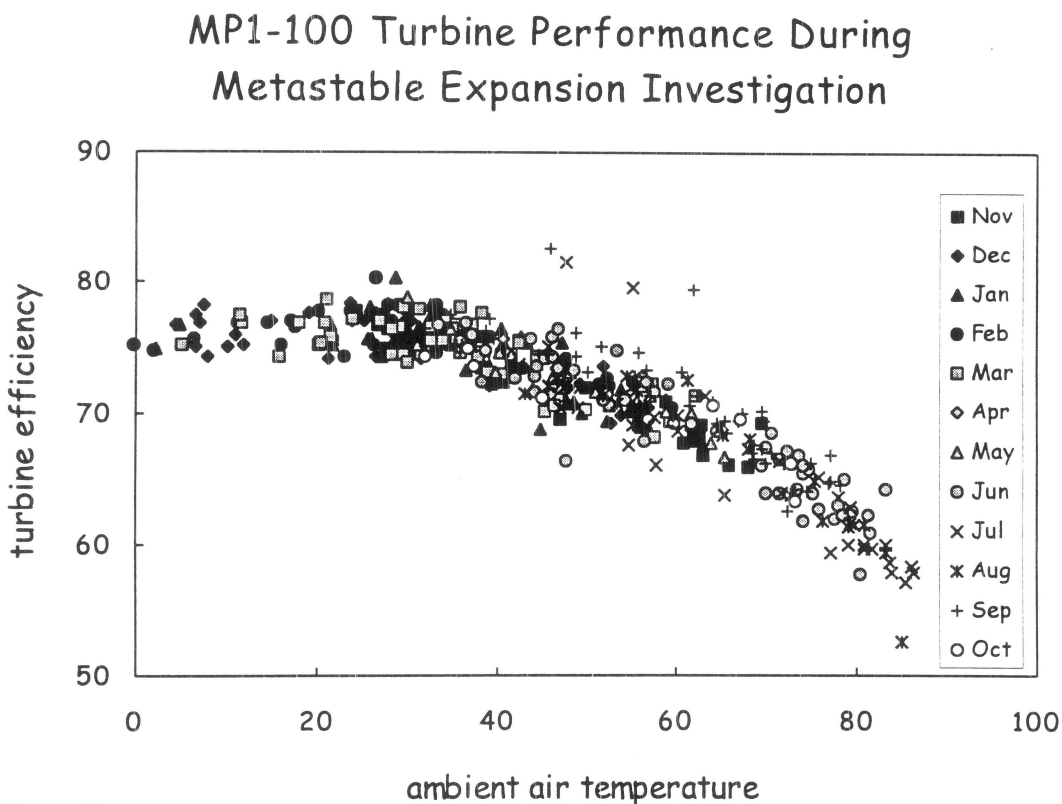

Figure 3