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THE USE OF ASPEN IN THE ANALYSIS OF THERMODYNAMIC CYCLES

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Summary

In support of a number of programmatic activities of the Department of Energy (DOE) at the Idaho National Engineering Laboratory, analysis of the performance of low-temperature binary Rankine cycles for electrical power generation and estimation of the cost of the required equipment have been important technical areas for some time. In the past, these functions had been performed using separate computer programs designed for specific applications. Significant economies could be accomplished if it were possible to use a single computer program for all applications. In performing cycle analysis and cost estimation for the recovery of low-temperature thermal energy from the Advanced Test Reactor (ATR) at INEL, the ASPEN program was used, since it appeared to have the required capabilities.

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DISCLAIMER

The equipment modeled by ASPEN consists of a turbine, a pump, a condenser, a working fluid preheater, and a boiler. The thermodynamic properties of the working fluid were computed using the conformal solution theory version of the Benedict-Webb-Rubin equation of state.

Four thermodynamic cycles were considered, with isobutane, propane, R-12, and R-22, respectively, as working fluids. The net cycle power and thermal efficiencies were essentially equivalent for the four cycles, with isobutane giving the best results overall. However, a preliminary economic evaluation, based on investment per kilowatt, revealed that a system using R-12 as a working fluid would be significantly less expensive than one based on the other fluids.

It was concluded that ASPEN is a useful tool for thermodynamically and economically evaluating Rankine cycles for power production. Furthermore, thermodynamic performance alone, whether based on an elementary first law analysis or on a more sophisticated second law analysis, does not necessarily define an economically optimum system design.

THE USE OF ASPEN IN THE ANALYSIS OF THERMODYNAMIC CYCLES

1. Introduction

Until the advent in 1973 of high energy costs in the United States, there was little incentive to produce electricity or other high grade forms of energy from low-temperature (375-500 K) heat sources. In recent years, the rapidly-escalating price of energy in the United States relative to the fixed costs of investment has rendered the economics of power generation from low temperature sources considerably more favorable. Because the choice of a Rankine cycle working fluid can affect the usable power production by a factor of two or more, there is a need for a flexible analytical tool that can be used to screen working fluids and optimize the operating conditions. Of considerable advantage would be the capability to screen and optimize on the basis of the economic feasibility of the various investment options considered.

ASPEN would appear to be such a tool. Accordingly, when a recent project was funded at the Idaho National Engineering Laboratory (INEL) to design and prepare a cost estimate for a Rankine cycle to recover energy that is presently discarded during operation of the Advanced Test Reactor (ATR), ASPEN was used to perform a preliminary analysis and cost estimate. This paper will discuss this study and offer conclusions as to the usefulness of ASPEN in performing such studies.

2. Description of Equipment

Figure 1 presents a flow diagram of the proposed ATR energy recovery system. As can be seen, the system consists of a pump, a turbine, and four heat exchangers. The need for the superheater and the regenerator is generally based on whether they increase cycle efficiency enough to offset the fixed costs of the added heat exchangers. Thus, the system configuration itself can be subject to economic studies.

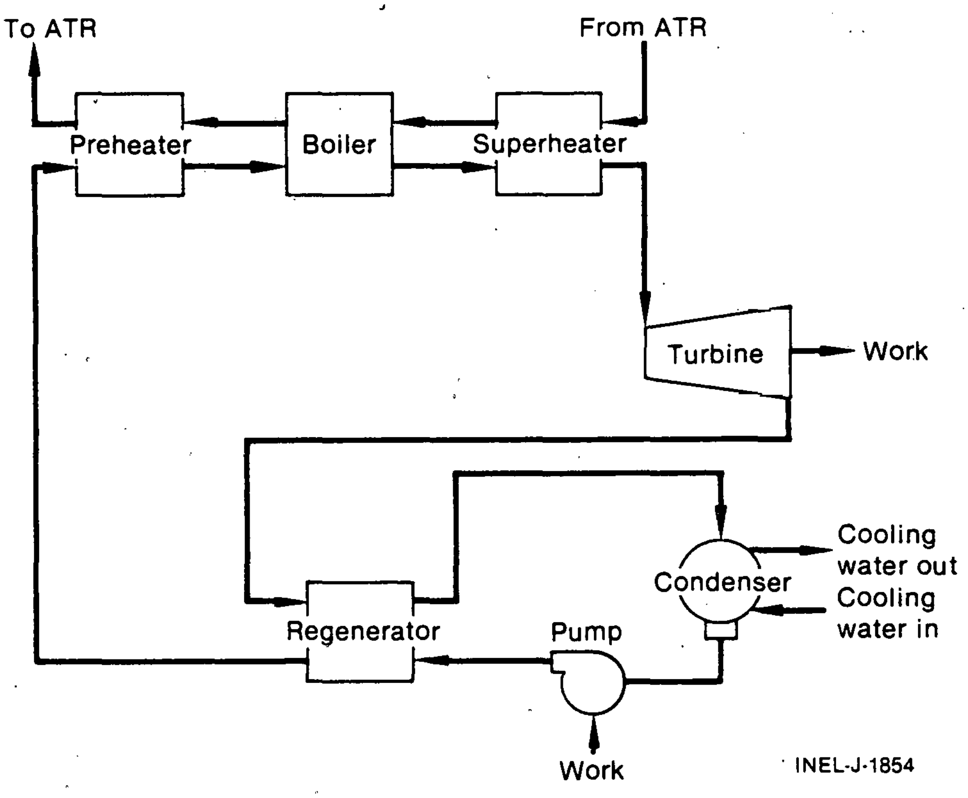

Figure 1. ATR Energy Recovery System

The heat source for the system is sensible heat from the primary coolant loop of the ATR. Constraints on the operation of ATR determined the entering temperature of the heat source and the total energy removed. Also specified was the temperature of the cooling water entering the condenser.

3. ASPEN Modeling Considerations

The equipment constituting the proposed power recovery facility was modeled using the ASPEN unit operations blocks COMPR, PUMP, and HEATER. As could be surmised, the COMPR block models a compressor, which was operated in the turbine mode. The pump was assumed to be a centrifugal pump and was modeled using the PUMP block. The HEATER block was used to model the condenser, the regenerator, the preheater, the boiler, and the superheater. For sensitivity studies involving removal of the regenerator or superheater, the heat transfer rate and working fluid pressure drop for the heat exchanger in question would be set to zero.

Flowsheet convergence is needed for this system because of the feedback of heat in the regenerator and because of the working fluid loop being closed. With temperatures for the source and the sink, working fluid pressure drops in the heat exchangers, and working fluid mass flow rate specified, the working fluid loop was torn at the outlet of the boiler to allow convergence.

The thermodynamic properties of the working fluids were modeled in the ASPEN calculations using the option set SYSOP5, which is based on Starling's conformal solution theory Benedict-Webb-Rubin equation of state. All systems modeled were pure components, either a hydrocarbon (propane or isobutane) or a refrigerant (R-12 or R-22).

4. Analysis of Computed Results

Because the source code of ASPEN was unavailable, the initial effort was devoted to assuring that computed results from ASPEN were consistent with computed results from a reference computer program that uses the same equation of state as was used for the ASPEN calculations. Table I compares the calculated turbine work for propane and isobutane. The generally good agreement indicates that the ASPEN results are consistent with the equation of state used.

TABLE I

CALCULATED TURBINE WORK FOR PROPANE AND ISOBUTANE

Fluid	Turbine Work (ASPEN) (J/kg)	Turbine Work (Reference)(J/kg)
Propane	39000	39100
Isobutane	45600	46500

Four thermodynamic cycles were considered, with isobutane, propane, R-12 and R-22, respectively, as working fluids. None of the systems utilized superheat, and only the isobutane system utilized regeneration. (These choices of superheat and regeneration were predetermined based on earlier screening calculations not reported here.)

Table II presents pertinent performance parameters for the four systems. The net cycle power and thermal efficiencies are essentially equivalent for the four cycles, considering the inaccuracies inherent in the calculations, although the best balance of net power and thermal efficiency was obtained with isobutane. However, one might elect to use R-22 to eliminate the investment cost of fire prevention measures. Other considerations would include the higher system pressure for R-22, which would increase the equipment costs. Sorting out some of these considerations is possible using ASPEN's cost blocks and the economic analysis package.

TABLE II

PERFORMANCE OF POWER RECOVERY SYSTEMS

Fluid	Condenser Pressure (kPa)	Net Power (MW)	Thermal Efficiency (percent)
Isobutane	270	9.3	7.8
Propane	820	9.1	7.5
R-12	540	9.0	7.7
R-22	920	9.1	7.8

A preliminary economic evaluation of the four cycles shown was completed, using investment per kilowatt as a criterion. A complete economic evaluation was not performed because of constraints of time. The costs for all the components used, except for the turbine, were estimated using ASPEN. Turbine costs were obtained separately, since ASPEN does not provide turbine costs. For the same four systems described above, Table III presents the equipment costs. Note that the cost of a fire protection system is not included for the two hydrocarbons, and that their investment costs would

TABLE III

ASPEN EQUIPMENT COSTS

	Costs, $							
Fluid	Pump	Preheater	Boiler	Turbine	Condenser	Regenerator	Total	$/KW
Isobutane	71,370	425,200	4,953,600	2,984,000	8,873,400	160,280	17,468,000	1900
Propane	127,800	341,400	3,018,400	3,027,000	8,662,420	--	15,177,000	1700
R-12	73,567	301,200	3,171,700	2,966,000	6,340,900	--	12,853,000	1400
R-22	95,590	368,400	3,828,300	3,031,000	8,260,250	--	15,484,000	1700

necessarily be higher than shown. Based on capital costs per kilowatt, the clear winner is R-12. Referring to Table II, we see that selecting R-12 loses very little in terms of thermal efficiency or net power.

5. Conclusions

The following conclusions result from this study:

1. ASPEN is a useful tool for thermodynamically evaluating the performance of Rankine cycles for power production.

2. ASPEN facilitates the economic evaluation of thermodynamically promising systems.

3. Thermodynamic performance alone, whether based on elementary first law considerations on more sophisticated second law considerations, does not necessarily lead to an economically optimum system design.