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RANKINE: a Computer Software Package for the Analysis and Design of Steam Power Generating Units

A software package has been developed for the analysis of steam power systems. Twenty-eight configurations are considered, all based upon the simple Rankine cycle with various additional components such as feedwater heaters and reheat legs. The package is demonstrated by two examples. In the first, the optimum operating conditions for a simple reheat cycle are determined by using the program. The second example involves calculating the exergetic efficiency of an actual steam power system.

Introduction

Nearly all major electric-generating power systems run through a series of processes which is based upon the theoretical thermodynamic cycle called the Rankine cycle. Because the Rankine cycle is the basis for steam power cycles, its analysis is vital to the design of power systems and to ensuring their proper operation. By introducing additional components, such as feedwater heaters or reheat legs, or adjusting the operating temperatures and pressures, a Rankine cycle analysis can be used to maximize the thermal efficiency and exergetic efficiency (second law effectiveness) within the constraints of turbine exit quality and pump capacity. The process of analyzing these Rankine cycles and attempts at optimizing the operating conditions can be very complex as well as time consuming. Such an analysis dictates the use of the computer. A software package (RANKINE) has been designed and tested which will solve a wide range of Rankine cycle problems very quickly. This software package is the subject of this paper.

Another use of the software package is in the instruction of undergraduate mechanical engineering students. Because the Rankine cycle is the basis for steam power cycles, it is a primary topic covered in an intermediate thermodynamics course. In order to provide the students with a feeling for how the ideal Rankine cycle may be modified in order to model any actual steam power cycle, a large number of examples need to be worked. With the RANKINE software package, the students will be able to gain a feeling for actual steam power cycles in a reasonable time period.

Previous software packages dealing with Rankine or modified Rankine cycles fall into one of three groups. There have been some very simple programs developed which can be run on hand-held calculators (Whitehouse, 1984). These are normally restricted to considering only the simple Rankine cycle and hence do not provide a realistic analysis of the power plant. The second group involves software packages that run on micro- or minicomputers. Preston et al. (1973) have written a program for the PDP-8 computer which analyzes the operation of the Rankine cycle for classroom use. Unfortunately, this second group is also restricted to only the simplest steam power cycles such as the Rankine or reheat cycle since the primary use of these programs is for classroom instruction. Finally, there are some massive computer programs available for the analysis of actual steam power plants, but these are

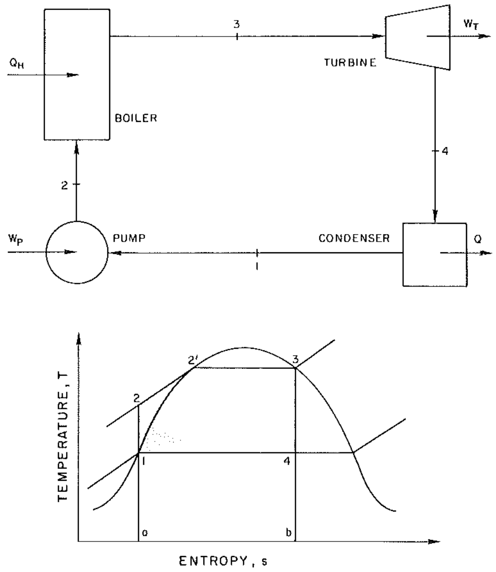

Fig. 1 The simple Rankine cycle

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often very costly to run and are designed for a specific power plant. Among these codes are Pepsi, SNYTHA, and Therm (Babin, 1985). Recently, Rosen and Scott (1985) have modified the Aspen Plus code for energy-exergy analysis. A modular technique was employed by Sonnenschein (1982) to perform calculations involving power station energy balances and plant efficiency. The RANKINE program is sufficiently flexible to analyze a number of different power plants and is also sufficiently simple to be used for instructional purposes. The Rankine software package was developed by the authors from scratch using a cycle solution methodology employed by one of the authors in the classroom.

This paper continues by providing a short theoretical background on the Rankine cycle, followed by a detailed description of the designed computer program. This will include an outline of the overall structure of the program, details of each subroutine, the operating structure of the program (with appropriate flow charts), and a discussion on the acquisition of the physical properties of the working fluid (steam). The paper concludes by employing the software package to optimize the thermal efficiency of a simple reheat cycle subject to a constraint on the exit quality of the turbines. Finally, the software package is demonstrated by conducting a second law analysis on a more complicated steam power system.

Theoretical Background

The theoretical Rankine cycle is shown in Fig. 1 in a schematic diagram as well as a temperature-entropy diagram. In the ideal Rankine cycle the process from 1-2 represents a reversible isentropic pumping process, from 2-3 is a constant pressure transfer of heat in the boiler, from 3-4 is a reversible isentropic expansion in the turbine, and from 4-1 is a constant-pressure transfer of heat in the condenser. The temperature-entropy diagram shows the possible states at each node but due to friction or heat losses these states may not be as the diagram indicates. The area denoted by a-2-2′-3-b-a indicates the heat transferred to the working fluid Q_H (steam in this case) and the area denoted by a-1-4-b-a indicates the heat transferred from the fluid Q_L. The net work is represented by the difference in the heat added and the heat rejected, or the portion of the diagram which is shaded.

The major components of the Rankine cycle are:

(*i*) *Boiler*—converts the working fluid of the system from the liquid state into a vapor state through heat addition.

(*ii*) *Turbine*—converts the available energy of the steam into mechanical energy by an expansion process.

(*iii*) *Condenser*—converts the working fluid of the system from the vapor state into a liquid state with rejection of heat.

(*iv*) *Pump*—raises the pressure of working fluid in liquid state.

(*v*) *Feedwater Heater*—mixes extracted stream from the turbine with the liquid from the condenser.

In modifying the simple theoretical Rankine cycle for steam power use, a reheat leg is often employed. This uses steam extracted off the turbine, passed back through the boiler and finally expanded through a second turbine. The reheat cycle is used to increase efficiency with higher pressures but avoids high moisture in the turbine.

When a modified Rankine system is used to model an actual steam power cycle a number of deviations from ideal operation must be incorporated. The principal losses considered in the software package are:

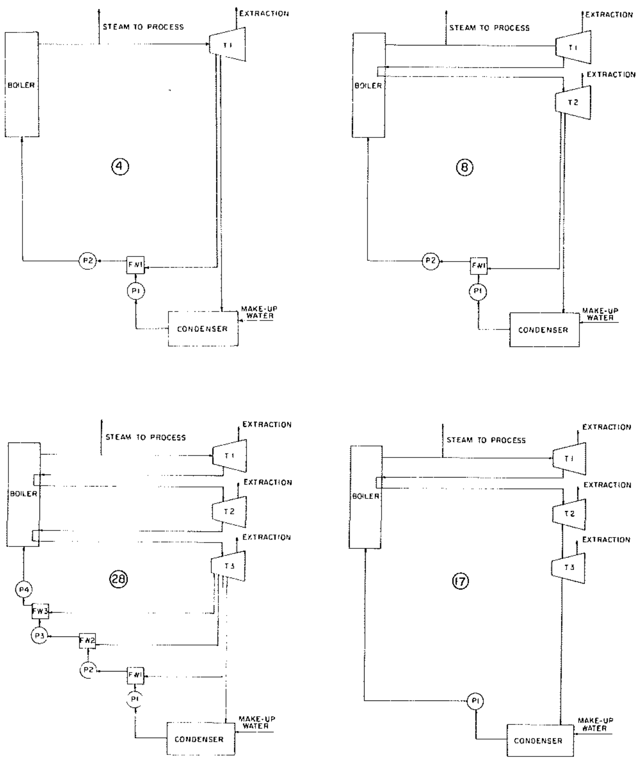

Fig. 2 Examples of cycle configurations

(*i*) turbine losses
(*ii*) pump losses
(*iii*) condenser losses
(*iv*) piping losses, both pressure losses and heat losses

These deviations from ideal performance are all incorporated into the program using the method outlined by Van Wylen and Sonntag (1974). Shaft and valve leakages are not accounted for in the program.

Description of the Software Package

The main program of the software package has been designed to analyze 28 different cycle configurations. Some of these configurations are shown in Fig. 2 and range in complexity from the simple Rankine cycle to a steam power cycle that includes three turbines, two reheat legs, and three feedwater heaters. Some generality of the program is lost by allowing a maximum of only three feedwater heaters, since the standard in today's large control station power cycles is seven feedwater heaters. For all the configurations extraction of process steam has been accounted for with makeup water being added at the condenser. For each cycle, the exit conditions of the boiler and the exit pressure of the turbine(s) are required inputs.

Once the cycle to be analyzed has been selected, a noding of the cycle is carried out. Beginning with the condenser, a node is identified and numbered after every device. The piping between components is considered a device so that node 1 is at

Nomenclature

E = exergy
h = enthalpy
L = fluid state index
P = pressure
P_I^* = dimensionless intermediate pressure
Q = quality
Q_H = heat added
Q_L = heat rejected
s = entropy
T = temperature
W = work
ϵ = exergetic efficiency

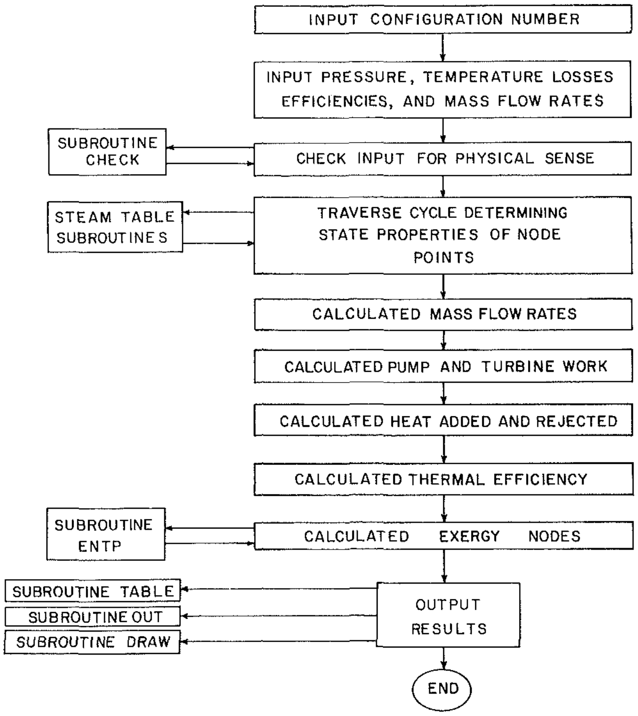

Fig. 3 Flow chart of RANKINE

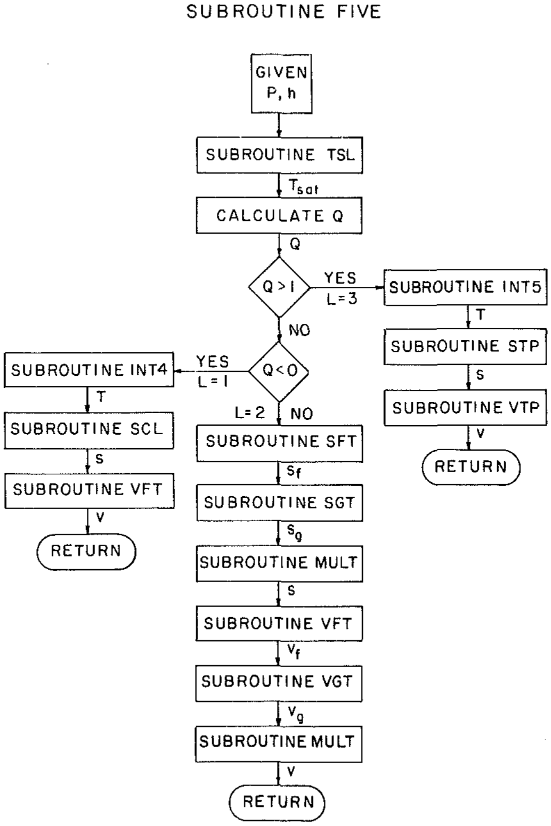

Fig. 5 Flow chart of subroutine FIVE

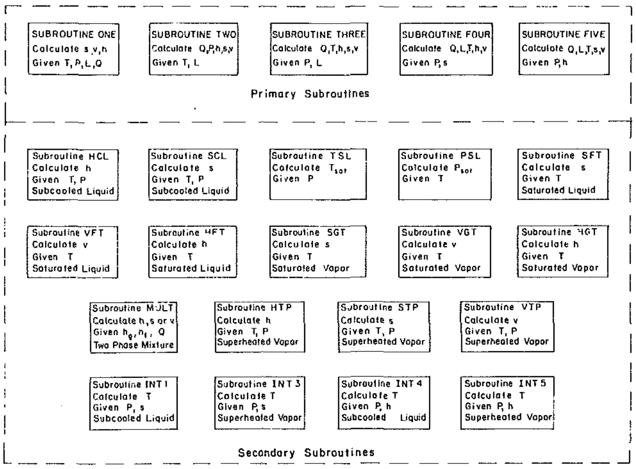

Fig. 4 Steam table subroutines

the exit of the condenser, but node 2 is at the entrance to the first pump. This is, of course, the exit of the "pipe device." After the nodes have been numbered, the cycle is traversed, using the appropriate thermodynamic relations to obtain the state variables at the next node. At this time the required inputs of temperature T, pressure P, quality Q, and fluid state L are made. The fluid state index L takes on the values of 1 for subcooled liquid, 2 for two-phase mixture, and 3 for superheat vapor. Once all of the state variables are specified at each node the calculations for net work, thermal efficiency, and exergy can be performed. The results are all printed out in tabular form and the corresponding temperature–entropy diagram is drawn. Once all of the state variables are specified at each node the calculations for net work, thermal efficiency, and exergy can be performed. The results are all printed out in tabular form and the corresponding temperature–entropy diagram is drawn.

A key element in determining the state variables at each node is employing the appropriate equation of state or fundamental relation for the working fluid. The equation of state for steam is represented by the steam tables. The steam table routines of RANKINE were programmed from the equation derived in the Keenan and Keyes edition of the *Steam Tables* (1947).

A flow chart of the overall operation of the software package is shown in Fig. 3. In Fig. 4 a description of the Steam Table Subroutines is provided. The interaction of the Steam Table Subroutines is somewhat unique and an example is given in the flow chart of Fig. 5.

Although this software package is multipurpose, it does have certain limitations. The numerical methods used to calculate the steam table properties introduce considerable errors whenever the pressure is greater than the critical pressure. Therefore, the maximum allowable input pressure is 22.09 MPa. This prohibits use of the program to simulate systems with supercritical boilers. The maximum allowable temperature input is 1300°C. The software package also fixes the state at the exit of the condenser and exit of a feedwater heater to be saturated liquid. The input values for pressure and heat losses can be either positive or negative, but the pressure loss cannot exceed the pressure at the entrance of the pipe and the heat loss cannot exceed the enthalpy at the entrance of the pipe. Finally only open feedwater heaters can be incorporated, as closed feedwater heaters which require iterative solution schemes cannot be solved with RANKINE.

Demonstration of the Software Package

To demonstrate the usefulness of RANKINE for power plant design, we first consider the simple reheat cycle specified as configuration #7 and shown in Fig. 6. The design problem faced in considering the reheat cycle is to select the intermediate pressure, that between the turbines, so that the thermal efficiency η_{th} is maximized while the exit quality of

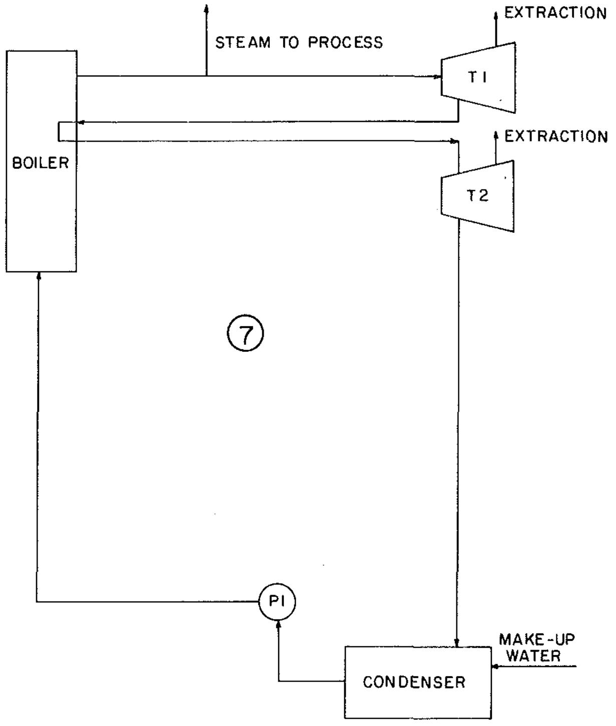

Fig. 6 Simple reheat cycle

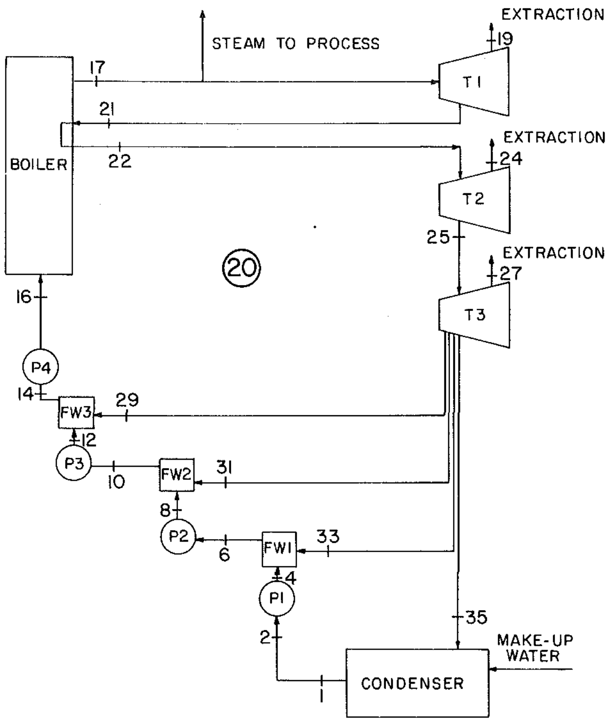

Fig. 8 Actual steam power system

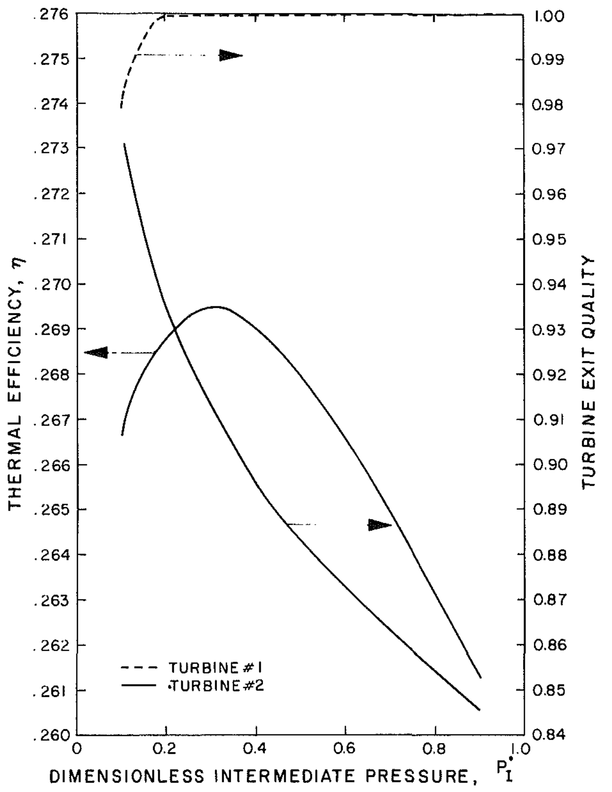

Fig. 7 Thermal efficiency and turbine exit qualities for reheat cycles

the turbine is maintained above 0.9. This optimization can be done very easily and quickly using RANKINE. To simulate actual conditions, pump and turbine efficiencies are taken to be 85 percent. Further, it is assumed that the temperature at the exit of the reheat leg is 80 percent of that at the exit of boiler. The boiler exit conditions are set at 2 MPa and 100°C superheat and the condenser pressure is 0.01 MPa. A dimensionless intermediate pressure is defined as

$$P_I^* = \frac{P_{\text{Intermediate}} - P_{\text{Condenser}}}{P_{\text{Boiler}} - P_{\text{Condenser}}} \qquad (1)$$

and the computer program is run over a range of values of P_I^*. The results of these computer runs are shown in Fig. 7. The computer time required for these runs is very small with the program residing on a main-frame computer such as an IBM3033 or a VAX machine.

The first use of Fig. 7 is to determine the range of P_I^* for which the constraint of turbine exit quality greater than 0.9 is satisfied for both turbines. From the graph this range is seen to be 0.1 to 0.37. Now restricting our attention to this range of P_I^*, we seek to maximize the thermal efficiency. Fortunately the global maximum of η_{th} occurs within this range of $P_I^* = 0.315$. This is in fair agreement with the rule of thumb used for optimum reheat pressure being 20–25 percent of throttle for large single reheat power plant cycles. For the given pressures of the boiler and condenser this translates to an actual pressure of 0.637 MPa. By operating the reheat cycle at this intermediate pressure its maximum efficiency will be achieved.

Another question which may arise involving the reheat cycle concerns the reheat leg exit temperature. Normally, this temperature is some fraction of the boiler exit temperature (80–85 percent), the standard being 1000°F maximum reheat temperature. In the example just presented it was taken as 80 percent. A question one may well ask is whether the improvement in the thermal efficiency is worth the effort to raise this percentage to 85 or 90 percent. To increase this percentage usually involves a capital expenditure, such as an additional heat exchanger pass. The RANKINE package can be used for decision-making purposes via cost-worth analyses.

Finally, the RANKINE software package can be used to conduct a second law analysis of a power system. To demonstrate this analysis, configuration #20, shown in Fig. 8, is employed, which does a reasonable job of modeling the power plant schematic given by Babcock and Wilcox in their handbook (1978).

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                              ***** CONFIGURATION 20 *****
NODE      T(C)      P(MPA)    L       Q     S(KJ/KG K) H(KJ/KG) V(KG/M**3) EXERGY(KJ/KG)
  1       32.9      0.0050    1     *****     0.4763    137.88    0.0010        0.6
  2       32.9      0.0050    1     *****     0.4763    137.88    0.0010        0.6
  3       32.9      0.0170    1     *****     0.4763    137.89    0.0010        0.6
  4       32.9      0.0170    1     *****     0.4763    137.89    0.0010        0.6
  5       56.6      0.0170    1     *****     0.7876    236.78    0.0010        6.7
  6       56.6      0.0170    1     *****     0.7876    236.78    0.0010        6.7
  7       56.6      0.0660    1     *****     0.7876    236.84    0.0010        6.8
  8       56.6      0.0660    1     *****     0.7876    236.84    0.0010        6.8
  9       88.4      0.0660    1     *****     1.1732    370.07    0.0010       25.1
 10       88.4      0.0660    1     *****     1.1732    370.07    0.0010       25.1
 11       88.4      0.1830    1     *****     1.1733    370.22    0.0010       25.2
 12       88.4      0.1830    1     *****     1.1733    370.22    0.0010       25.2
 13      117.4      0.1830    1     *****     1.4991    492.65    0.0011       50.6
 14      117.4      0.1830    1     *****     1.4991    492.65    0.0011       50.6
 15      120.2     22.0900    1     *****     1.5026    519.92    0.0011       76.8
 16      120.2     22.0900    1     *****     1.5026    519.92    0.0011       76.8
 17      538.0     22.0900    3     *****     6.2290   3338.04    0.0143     1486.4
 18      538.0     22.0900    3     *****     6.2290   3338.04    0.0143     1486.4
 19      538.0     22.0900    3     *****     6.2290   3338.04    0.0143     1486.4
 20      289.4      3.7200    3     *****     6.3564   2940.93    0.0621     1051.4
 21      289.4      3.7200    3     *****     6.3564   2940.93    0.0621     1051.4
 22      538.0      3.7200    3     *****     7.2327   3532.45    0.0982     1381.8
 23      538.0      3.7200    3     *****     7.2327   3532.45    0.0982     1381.8
 24      538.0      3.7200    3     *****     7.2327   3532.45    0.0982     1381.8
 25      284.4      0.5050    3     *****     7.3977   3031.52    0.5027      831.7
 26      284.4      0.5050    3     *****     7.3977   3031.52    0.5027      831.7
 27      538.0      0.5050    3     *****     8.1818   3562.75    0.7389     1129.2
 28      182.6      0.1830    3     *****     7.4746   2836.65    1.1369      613.9
 29      182.6      0.1830    3     *****     7.4746   2836.65    1.1369      613.9
 30       98.0      0.0660    3     *****     7.5521   2676.70    2.5686      430.8
 31       98.0      0.0660    3     *****     7.5521   2676.70    2.5686      430.8

 32       56.6      0.0170    2     0.956     7.6472   2498.98    8.5152      224.8
 33       56.6      0.0170    2     0.956     7.6472   2498.98    8.5152      224.8
 34       32.9      0.0050    2     0.916     7.7287   2357.65   25.8099       59.2
 35       32.9      0.0050    2     0.916     7.7287   2357.65   25.8099       59.2
THE WORK OF PUMP          1IS -1.2215804E-02(KW)
THE WORK OF PUMP          2IS -5.2589539E-02(KW)
THE WORK OF PUMP          3IS -0.1353554    (KW)
THE WORK OF PUMP          4IS  -27.26770    (KW)
THE WORK OF TURBINE         1IS   397.1057    (KW)
THE WORK OF TURBINE         2IS   500.9348    (KW)
THE WORK OF TURBINE         3IS   628.2141    (KW)
THE NET WORK IS   1498.787    (KW)
THE HEAT ADDED IS   3409.638    (KW)
THE HEAT REJECTED IS  -1910.851    (KW)
THE THERMAL EFICIENCY IS  0.4395736
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Fig. 9 Computer results for Configuration 20

The results of the computer run are shown in Fig. 9. The authors define an exergetic efficiency as

$$\epsilon = \frac{\text{exergy and work produced}}{\text{exergy and work used}} \tag{2}$$

This is a somewhat different efficiency than the second law effectiveness defined by Bejan (1982) and Paolino and Burghardt (1982). The advantage of using the exergetic efficiency as defined by the authors in steam power cycle analyses is that the exergy used in delivering process or extracted steam can be easily incorporated. Exergy and work produced connote the outputs of the cycle such as process and extracted steam and turbine work. Exergy and work used include the exergy supplied from the boiler and reheat legs. For the problem being considered we have

$$\epsilon = \frac{W_{T1} + W_{T2} + W_{T3}}{(\Delta E)_{\text{boiler}} + W_{p1} + W_{p2} + W_{p3} + W_{p4} + (\Delta E)_{\text{reheat}}} \tag{3}$$

The terms $(\Delta E)_{\text{boiler}}$ and $(\Delta E)_{\text{reheat}}$ represent the exergy change of the steam as it passes through the boiler or reheat leg. That is,

$$(\Delta E) = h_{\text{out}} - h_{\text{in}} - T_0(s_{\text{out}} - s_{\text{in}}) \tag{4}$$

where T_0 is taken at 298 K. For the calculation of exergy at a node the definition is used

$$E = h - h_0 - T_0(s - s_0) \tag{5}$$

where h_0 and s_0 are taken for saturated liquid at 298 K. From Fig. 9 we can thus determine the exergetic efficiency as

$$\epsilon = \frac{397.11 + 500.93 + 628.21}{1409.6 + 0.0122 + 0.0526 + 0.135 + 27.268 + 330.4} = 0.864 \tag{6}$$

Conclusions

A software package called RANKINE has been developed to analyze 28 different steam power cycle configurations. The package allows for inefficiencies in the pumps and turbines and accounts for pressure losses and heat losses in the piping.

Results are provided in terms of the thermodynamic state properties before and after each device, the work of the pumps and turbines, heat added to and rejected by the cycle, and the overall thermal efficiency of the cycle. Along with these results, drawings of the cycle and the temperature-entropy diagram are also provided as output.

The software package has been shown to be useful in power plant design and analysis through calculations performed for two cases. The package may also be used for classroom demonstration.

Authors' Note

For educational purposes, the authors are willing to make the RANKINE software package available to interested parties at no charge. The program is currently running on a VAX/VMS system in Fortran 77. The KERMIT file transfer program will be used to transfer the package to a diskette for either IBM or DEC compatible machines.

References

Babcock and Wilcox, 1978, *Steam/Its Generation and Use*, 39th ed., Babcock and Wilcox, New York.

Babin, T., 1985, Personal Communication.

Bejan, A., 1982, *Entropy Generation Through Heat and Fluid Flow*, Wiley, New York.

Keenan, J. H., and Keyes, F. G., 1947, *Thermodynamic Properties of Steam*, Wiley, New York.

Paolino, M. A., and Burghardt, M. D., 1982, "Energy Conservation and Second Law Efficiency," ASME JOURNAL OF ENGINEERING FOR POWER, Vol. 104, pp. 241-246.

Preston, R., Harmer, D. S., Carlson, R. W., and Wrege, D. E., 1973, "Minicomputer Program for Evaluating Rankine Cycles Using Steam Tables," *DECUS Proceedings*, San Francisco, pp. 279-282.

Rosen, M. A., and Scott, D. S., 1985, "The Enhancement of a Process Simulator for Complete Energy-Exergy Analysis," AES-Vol. 1, ASME Winter Annual Meeting, Miami Beach, FL.

Sonnenschein, H., 1982, "A Modular Optimizing Calculation of Power Station Energy Balance and Plant Efficiency," ASME JOURNAL OF ENGINEERING FOR POWER, Vol. 104, pp. 255-259.

Van Wylen, G. J., and Sonntag, R. E., 1978, *Fundamentals of Classical Thermodynamics*, 2nd ed., Wiley, New York.

Whitehouse, G. D., 1984, Personal Communication.