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GEOTHERMAL POWER PLANT CYCLES

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PROGRAM GEOTHM A THERMODYNAMIC PROCESS PROGRAM FOR GEOTHERMAL POWER PLANT CYCLES*

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ABSTRACT

Program GEOTHM is a thermodynamic process program now under development for the LBL Geothermal Energy Program. To date, the program development has centered upon the modeling of working fluid properties, developing thermodynamic process models, and modeling the design performance of geothermal power plants. When the program is completed, it will be able to optimize a power plant or refrigeration plant for minimum cost power or refrigeration. Furthermore, operation of the thermodynamic cycles at off design conditions will be able to be simulated. Program GEOTHM is currently able to calculate several types of geothermal power cycles using a wide variety of working fluids.

INTRODUCTION

GEOTHM is a thermodynamic process program which may be applied to various power and refrigeration cycles. The program is designed for use in connection with the Lawrence Berkeley Laboratory Geothermal Energy Program. The program may be used with some modification on other power cycles such as: 1) fossil fuel plants, 2) nuclear plants, 3) MHD plants, and 4) solar energy cycles. Refrigeration cycles may also be calculated. When the development of GEOTHM is complete, it will be able to calculate power plant or refrigeration plant costs. The ultimate goal in the development of the program is to be able to optimize the thermodynamic cycle for minimum capital cost or minimum unit cost for energy (in a power cycle) or refrigeration. GEOTHM will, when completed, be able to model the thermodynamic behavior of a given power plant (or refrigerator) when it is running at off design conditions. The program could be used to calculate the effect of changes of cycle parameters on the thermodynamics of the cycle. (For example, what happens to a power plant when the U factor in a major heat exchanger drops due to fouling.)

This paper will report the progress which has been made to date in the development of GEOTHM. The major effort has been expended in the following three areas: 1) thermodynamic working fluid properties calculations, 2) thermodynamic cycle calculations, and 3) input,

output, and data handling. Little effort has been expended in the area of component cost calculation or cycle cost optimization.

WORKING FLUID PROPERTIES

The calculation of working fluid properties is the heart of program GEOTHM. Over half of the subroutines in the program are devoted to this process. The working fluid properties are calculated using several complicated equations of state rather than interpolating tabular data. The reasons for this are as follows: 1) the tables require much extra memory, 2) the tables are often inaccurate and inconsistent, 3) tabular data is often not available in regions near the critical point or in regions where the pressure is above the critical pressure.

The working fluid phase diagram is divided into four regions by the program (see Fig. 1). Region 1 is an incompressible liquid

Fig. 1. Thermodynamic fluid regions.

region; Region 2 is the two phase region inside the liquid vapor dome. Region 3 is a dense vapor region which applies on the gas side of the liquid vapor dome and applies to supercritical regions which lie at temperatures above the critical isotherm. Region 4 is the ideal gas region where the density is very low compared to the density at the critical point and the compressibility factor Z approaches 1. The computer program has a subroutine which is responsible for calculating fluid properties in each of the four regions. In some cases the regions overlap. Regions 1a and 1b are parts of Region 1 where the equations of state used in Region 3 may be used. Region 3 equations of state may be used in Region 4. The fluid region is selected by subroutine PROP. Subroutine PREP serves the function of defining the boundaries of the two phase region.

Given the liquid vapor dome boundaries, the equations of state in Regions 1, 2 and 4 are well defined and simple. Region 3 presents particular difficulties because of the non-linear nature of the equation of state. A general form of the equation of state is as follows:

$$P = Z \rho RT \quad (1)$$

where ρ the gas density $= \frac{1}{V}$, (kg m^{-3}), V the specific volume ($\text{m}^3 \text{kg}^{-1}$), P the pressure (N m^{-2}), T the temperature (K), and R the universal gas constant ($R = 8314.4$ divided by the molecular weight, $\text{J kg}^{-1} \text{K}^{-1}$). Z is a compressibility factor. In Region 3, Z has the limits $Z_c \leq Z < 5$. Z_c is the gas compressibility at the critical point. ($Z_c = P_c V_c / RT_c$ where P_c , V_c , and T_c are the P , V , and T at the critical point.)

The choice of equation of state for Region 3 was dictated by practical considerations. The Martin equation of state (two forms of it) is chosen because coefficients exist which can be used for various refrigerants. For light hydrocarbons, the Starling equation of state coefficients already exist. Much of the effort put into this program was devoted to making the various equations of state compatible with the method used to calculate thermodynamic state points. The equations of state used in the program are described in the next section.

At a thermodynamic cycle state point, it is useful to know P , the pressure (N m^{-2}), V , the specific volume ($\text{m}^3 \text{kg}^{-1}$), T , the tempera-

ture (K), H , the enthalpy (J kg^{-1}), and S , the entropy ($\text{J kg}^{-1} \text{K}^{-1}$). In general one should be able to calculate all five parameters knowing any two, but practical and thermodynamic considerations do not make this possible.

Within Region 3 the equations of state used will calculate P as a function of T and V or T and ρ . Subroutine PRES is programmed with two forms of the Martin equation of state and the Starling equation of state. Given P , T , and V plus the equation of state, one may calculate the deviation of H and S from the ideal gas values of H and S . This method is used by Downing¹, Milora², and Starling³. GEOTHM uses modified versions of Milora's² computer program subroutines. The ideal gas values of H and S may be calculated using a simple power series expansion. I suggest that the reader consult Refs. 1-3 for the ideal gas, specific heat, enthalpy, and entropy equations.

Subroutine PRES combined with ENTHIG, ENTRIG, HDEV, and SDEV permit one to calculate P , H , and S given V and T . If one is given P and T , V must be calculated iteratively using subroutine VOLUME which uses Newton's method for a single variable. The entropy and enthalpy subroutines are used to find S and H . When P and H are given, subroutine TOFHAP calculates T iteratively; when P and S are given, subroutine TOFSAP is used to calculate T . Then VOLUME and the entropy or enthalpy subroutines may be used to calculate the remaining variables V and S or V and H .

FLUID EQUATIONS OF STATE

A very general form of the equation of state was given in the last section (see Eq. 1). This form of the equation is inadequate for describing the behavior of the fluid because Z is a nonlinear function of V and T . This function is different for each fluid and is not easily calculated. In Regions 1 and 2, the whole concept of Eq. (1) breaks down. For ease of calculation, it is desirable to use much simpler equations of state in these regions. The same reasoning applies in Region 4.

In Region 3, empirical equations such as the Martin equation of state^{1,2} and the Starling equation of state³ are a convenient way to express the properties of the fluid. Both equations of state have the general

property of approaching the ideal gas equation of state when $V \rightarrow \infty$. At the critical point⁴ both equations of state have the property of

$$\left| \frac{\partial P}{\partial V} \right|_T = 0 \quad \text{and} \quad \left| \frac{\partial^2 P}{\partial V^2} \right|_T = 0.$$

A. TWO PHASE (LIQUID TO GAS) EQUATION OF STATE

The two phase region (Region 2) has the characteristic that when pressure is defined so is the temperature. Therefore, a knowledge of P and T is not enough to determine the state of the fluid in this region. In addition to P or T, one must know the quality of the fluid X. One may determine X if one knows P or T and H, S or V.

$$X = \frac{H - H_f}{H_{fg}} = \frac{S - S_f}{S_{fg}} = \frac{V - V_f}{V_{fg}} \quad (2)$$

where H_f , S_f , and V_f are H, S, and V of the liquid phase. H_{fg} , S_{fg} , and V_{fg} are the differences of H, S, and V between the gas and liquid phase.

Once the liquid-vapor dome is defined one can calculate the properties of the fluid in the two phase region. The program uses two ways of determining the fluid properties in the liquid-vapor dome. The first is to feed the properties in from the outside. If this is not properly done, convergence errors in Region 3 will occur in regions near the saturated vapor line and the critical point. A better way is to calculate the liquid-vapor dome using the equation of state used in Region 3.

Two methods are available for doing this. The first, which is used with the Martin equation of state,^{1,2} proceeds as follows. First, calculate the relationship between P_{SAT} and T_{SAT} (vapor pressure vs. temperature) using a relationship such as shown in Eq. (3).⁵

$$\ln(P_{SAT}) = A - B/T_{SAT} - C \ln(T_{SAT}) + D T_{SAT}^2 + E T_{SAT}^3 - F \ln(b - T_{SAT}) \quad (3)$$

The coefficients may be found by applying a least squares fit to measured data along the saturated liquid line. Next, one should calculate the liquid density using an equation like Eq. (4).⁵

$$\rho_f = \frac{1}{V_f} = \sum_{N=0}^{\infty} D_N \left(1 - \frac{T}{T_c}\right)^{N/3} \quad (4)$$

the D_N coefficient may be fitted by least squares to measured data. (Note that T_c is the critical temperature). The specific volume, enthalpy and entropy on the saturated vapor line may be calculated using the equation of state in Region 3 (using subroutines VOLUME, ENTHIG, HDEV, ENTRIG, and SDEV). H_{fg} , S_{fg} , H_f and S_f may be calculated using the Clausius Clapeyron relationship.

$$H_{fg} = T_{SAT} \left(\frac{\partial P}{\partial T} \right)_{V_{fg}}, \quad S_{fg} = H_{fg}/T_{SAT} \quad (5)$$

The values of enthalpy and entropy are then referenced to some zero condition. All of these processes take place in subroutine PROCAL.

The second method is to use fugacity to determine the vapor pressure as a function T.³ The lowest root in V and the highest root in V are the saturated liquid and saturated vapor specific volumes. From these values, one can determine the properties of the liquid-vapor dome. The second method is applicable when used with the Starling equation of state.³

B. INCOMPRESSIBLE LIQUID EQUATION OF STATE

This equation of state is characterized by the fact that P is independent of T, and V is very nearly independent of T and P. H and S can be derived from the following expressions:

$$\begin{aligned} dH &= VdP + Cp dT \\ dS &= (dH - VdP)/T \end{aligned} \quad (6)$$

For all practical purposes, H in the incompressible liquid region is the same as the saturated liquid value of H when $T_{SAT} = T$.

C. THE IDEAL GAS EQUATION OF STATE

The ideal gas state applies when ρ is small as the compressibility $Z \rightarrow 1$. The following equations apply to the ideal gas:⁴

$$P = \rho R T$$

$$H_2 - H_1 = \frac{\gamma}{\gamma-1} R (T_2 - T_1) \quad (7)$$

$$S_2 - S_1 = \frac{\gamma}{\gamma-1} R \ln \left(\frac{T_2}{T_1} \right) - R \ln \left(\frac{P_2}{P_1} \right)$$

where R is the universal gas constant divided by the gas molecular weight and $\gamma = C_p/C_v$, the ratio of specific heats.

D. THE MARTIN EQUATION OF STATE

The Martin equation of state,⁵ which is used widely with refrigerants, yields good results in the supercritical and vapor regions of the fluids to which it has been applied. The equation has not been particularly successful in the dense liquid region except at reduced temperatures of 0.9 or above. The equation of state reduces to the ideal gas equation when $V \rightarrow \infty$, for large V the Martin equation of state has an appearance similar to Van der Waal's equation of state.

The Martin equation of state in the form of P as a function of T and V is as follows:

$$P = \sum_{N=0}^4 \frac{f_N(T)}{(V-b)^{N+1}} + f_5(T)e^{-aV} \quad (8)$$

$$+ f_6(T)e^{-2aV}$$

The last two terms f_5 and f_6 are only necessary when the equation of state is used near the critical point, $f_0(T) = T$.

The terms $f_1(T)$ through $f_6(T)$ may take two forms. The first form which is preferred by Martin and Downing^{1,5} is as follows:

$$f_N(T) = A_N + B_N T + C_N e^{-kT} \quad (8a)$$

The second form, which is preferred by Milora,² allows for an easy fit on the critical isotherm. The second form for $f_N(T)$ is as follows:

$$f_N(T) = f_N(T_c) + B_N (T - T_c) + C_N (e^{-kT} - e^{-kT_c}) \quad (8b)$$

where T_c is the critical temperature.

The deviation terms for H and S from the ideal gas will not be presented here. It is suggested that Refs. 1 and 2 be consulted. The

Martin equation of state may be used in GEOTHM on the following working fluids: the Downing form¹ R-11, R-12, R-13, R-14, R-21, R-22, R-23, R-113, R-114, R-500, R-502, and C-318; the Milora form² R-717 (ammonia) and R-22. Both the Milora and Downing forms of the R-22 (freon-22, CCl_2F_2) agree favorably with published ASHRAE data.⁷ The ammonia equation of state agrees with measured data extremely well.^{2,6}

E. THE STARLING EQUATION OF STATE

The Starling equation of state³ is a relatively new equation of state which works well in the compressed liquid region as well as the less dense gas region where the Benedict-Webb-Rubin⁸ (BWR) equation has worked well. The Starling equation of state has the same density relationship as the BWR equation of state. The Starling equation of state is:

$$P = \rho R T + (B_0 R T - A_0 - C_0/T^2 + D_0/T^3 - E_0/T^4) \rho^2 + (b R T - a - d/T) \rho^3 + \alpha (a + d/T) \rho^6 + C \rho^3/T^2 (1 + \gamma \rho^2) e^{-\gamma \rho^2} \quad (9)$$

where ρ is the density, and $A_0, B_0, C_0, D_0, E_0, a, b, c, d, \alpha$ and γ are constants of the equation of state. Figure 2 shows the multiple root nature of the Starling equation of state inside the liquid-vapor dome. (The Martin equation of state has a similar behavior on a P-V diagram.) As $\rho \rightarrow 0$, the Starling equation becomes the ideal gas equation of state.

Fig. 2. Starling-BWR equation of state - Isobutane.

The deviation terms for H and S from ideal gas are given in Ref. 3. In GEOTHM, the Starling equation can be applied to the following working fluids:³ methane, ethane, propane, N-butane, isobutane, N-pentane, isopentane, N-hexane, N-heptane, N-octane, ethylene, propylene, nitrogen, carbon dioxide, and hydrogen sulfide. Test cases with isobutane and propane yield good agreement with ASHRAE data.^{7,9}

The Starling equation of state can be applied to mixtures as well as single fluids. (GEOTHM is not currently equipped with this option.) No convergence difficulties have been found when it is used in our program, whereas the Martin equation of state has given us some difficulties. If LBL decides to curve fit other working fluids such as hydrogen or helium, the Starling equation of state will be used.

THERMODYNAMIC PROCESS CALCULATIONS

The calculation of thermodynamic cycles requires the calculation of many thermodynamic processes. Each major type of thermodynamic process is calculated using a separate subroutine. Thermodynamic processes are calculated by the OPRA subroutines which are controlled and called by subroutine CYCLE. These subroutines calculate the thermodynamics of components such as turbines (OPRA1), pumps (OPRA2), flash tanks (OPRA3 and OPRA4), heat exchangers (OPRA7) and so on. The thermodynamics of each component is reduced to its simplest form (for example, a turbine is basically an isentropic expander with one or more efficiency factors applied). The OPRA subroutines can be used alone or in combination to model rather complicated thermodynamic processes.

A. THE HEAT EXCHANGERS

The most difficult process component to model is the heat exchanger. Counter flow heat exchangers are used in the calculation, but with appropriate performance factors other types can be modeled as well. The heat exchanger calculations in a power plant may be divided into two main categories.

The first heat exchanger type is one where three of the four temperatures are known along with the average U factor, the pinchpoint ΔT , and the mass flow in one

stream. From this one may calculate the fourth temperature, the heat exchanger area, and the mass flow in the second stream. Typical examples of this kind of heat exchanger are a brine to secondary working fluid heat exchanger or an air cooled condenser found in simple binary geothermal power plants.¹⁰

The second heat exchanger type is one where only two temperatures are known (either the inlet or the outlet temperature of each stream), the heat exchanger U factor, the pinchpoint ΔT , and the mass flow in both streams. One may calculate the other two temperatures and the heat exchanger area. A typical example of this type of heat exchanger is a gas turbine regenerative heat exchanger or the heat exchangers which are widely used in cryogenic refrigeration cycles.

Both types of heat exchangers are solved iteratively by OPRA7. The area of each exchanger is calculated such that pinchpoint conditions are met. The heat exchanger is divided up into equal units of temperature or enthalpy (the former takes much less computer time because iteration is often eliminated in the equation of state). A mass flow rate is assumed in the Type 1 heat exchanger. A secondary stream temperature is assumed in the Type 2 heat exchanger. Increments of area are calculated by using the standard heat transfer equations. The U-factor is assumed to be constant throughout the heat exchanger. In most cases, this does not result in serious error.

B. PUMPS, COMPRESSOR AND TURBINES

The pump, compressor, or turbine in its simplest form is nothing more than an isentropic compression or expansion with the application of a suitable efficiency factor. The efficiency factors will vary depending on the type of device, the quality of the working fluid, the size or rating of the unit, and the percentage of design load at which the device is operating. As you might guess, most of OPRA1 and OPRA2 is devoted to calculating efficiency factors.

C. OTHER THERMODYNAMIC PROCESSES

The OPRA subroutines are capable of doing a number of other thermodynamic processes: an isenthalpic expansion is handled

by OPRA3, phase separation by OPRA4, mixing by OPRA9, and contact condensation by OPRA8. Subroutines OPRA5 and OPRA6 are used to calculate the effect of heat and friction losses in pipes. OPRA11, OPRA12, and OPRA13 are for air cooled condenser and cooling tower cycles. OPRA10 permits one to merge the end of one stream into the beginning of another stream (a simple cycle may be broken up into different fluid streams for ease of calculation).

D. POWER PLANT OUTPUT AND EFFICIENCY

Subroutine POWER performs the mass balance and energy balance on the thermodynamic cycle. The mass flow in each of the power plant streams is set by this subroutine. In a geothermal power plant, this subroutine calculates the power plant efficiency and the power plant yield per metric ton of water processed. The yield of the plant (kWh/ton) is a very meaningful figure of merit for a geothermal power plant.

Subroutine POWER may be used to calculate any of the power cycles. It is not suitable for refrigeration cycles. Before the calculation of refrigeration cycles can commence, one must rewrite this subroutine or create another subroutine especially for refrigerators.

INPUT, OUTPUT, AND DATA HANDLING IN GEOTHM

This section will briefly describe the input and output of data and the transformation of data within the program. Little detailed information will be presented here because the system of data input and output is being changed.

A. THE INPUT AND SUBSTITUTION OF DATA INTO THE PROGRAM

Data input into GEOTHM is handled by three subroutines: INPUT1, INPUT2, and INPUT3. The properties of the working fluids used in the thermodynamic cycles is put into GEOTHM by INPUT1. Currently five input formats are being used in INPUT1 for various equations of state.

INPUT2 has the sole function of feeding in the properties of the thermodynamic cycle. Each thermodynamic process is described on one computer card. The cards are fed into the program in the order in which the process calculation must proceed. INPUT3 inputs various points which may be substituted into a matrix generated by INPUT2. These points may be optimizable or non-optimizable in terms of system cost. INPUT3 also inputs various constants needed to do the thermodynamic calculations. (For example, the heat exchanger U factor may be such a constant.) Subroutine CHANGE substitutes data from matrices fed in by INPUT3 into the P, T, H, S and V matrix which is used by subroutine CYCLE to do the thermodynamic cycle calculations.

B. OUTPUT OF DATA FROM THE PROGRAM

The output of data from GEOTHM comes through several print and cal-comp plot routines. The data generated by GEOTHM are outputted from the program in metric units. AI units are used throughout the program for calculation, but the output uses a number of non-standard units because they are better visualized by the reader. For example, pressures are given in bar and specific volume is given in $\text{cm}^3 \text{g}^{-1}$.

PRINT1 prints out the working fluid properties. These include the critical constants, the equation of state constants, and the fluid properties on the liquid-vapor dome. PRINT2 prints the T, P, H, S and V at each cycle point. Also included in the PRINT2 output is the mass flow and type of fluid in each of the streams in the cycle. PRINT3 prints the thermodynamic properties of the cycle such as heat input, heat rejected, work out, work in, net work, cycle efficiency, and the yield of the plant. Other print routines are being written to print out the detailed parameters of the plant heat exchangers, turbines, pumps, and other components.

Several plotting programs have been used with GEOTHM. One plotting routine will plot isotherms of the equation of state on a P-V diagram (see Fig. 2); other plotting programs will make a P-V diagram, a T-S diagram, and P-H diagram of the thermodynamic

cycle. There is a plotting program which plots the yield of a geothermal power plant as a function of working fluid, input brine temperature, and turbine inlet P and T.

TEST THERMODYNAMIC CYCLES WHICH HAVE BEEN RUN BY GEOTHM

A number of geothermal cycles have been run in GEOTHM. These cycles include flashed steam cycles and binary cycles. Geothermal binary cycles have been run on the program with ammonia, R-22, isobutane, and propane as secondary working fluids. Cycles with air cooled condensers and water cooled condensers have been run.

Figure 3 shows a geothermal (hot water) power plant employing a simple binary cycle. This kind of a cycle was used to calculate a binary geothermal power plant with a net power of 10 megawatts. Figures 4 and 5 show computer generated P-V diagram and P-H diagram for the secondary working fluid part of the cycle shown in Fig. 3. Table 1 presents the cycle heat balance, the thermodynamic efficiency and the power yield from the geothermal well as calculated by GEOTHM for the simple isobutane power cycle shown in Fig. 3, 4, and 5.

The thermodynamic cycle shown in Fig. 4 and 5 is easily traceable on a standard P-H diagram for isobutane.^{7,9} The computer approach is more accurate, and it permits one to calculate a cycle like the one shown in Fig. 5 in less than one second of central processing time on the CDC-7600 at LBL. Short processing times are necessary in order to do the cost optimization. The program has reached the stage of development where valid thermodynamic comparisons can be made for various geothermal power cycles which utilize a wide range of working fluids.

Fig. 3. Simple binary geothermal power plant cycle.

Fig. 4. Thermodynamic cycle for geothermal power plant - pressure vs. volume.

Fig. 5. Thermodynamic cycle for geothermal power plant - pressure vs. enthalpy.

Table 1. The mass flow, heat balance, and cycle efficiency for the isobutane binary cycle shown in Fig. 3, 4, and 5.

Water input temperature	473.2 °K
Water mass flow	143.9 kg s ⁻¹
Isobutane mass flow	166.7 kg s ⁻¹
Air mass flow	5968.5 kg s ⁻¹
Air input temperature	298.0 °K
Net heat input	82.78 MW
Net heat rejected	72.45 MW
Turbine power out	13.53 MW
Fan and pump power in	3.20 MW
Net mechanical power	10.33 MW
Net electrical power	10.00 MW
Net cycle efficiency	11.94%
Power plant yield	19.30 kWh/ton

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