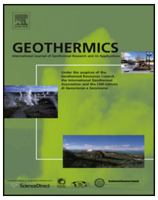
Geothermics 64 (2016) 187–195

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics



Improvement of calculating formulas for volumetric resource assessment

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ARTICLE INFO

Article history:
Received 13 January 2016
Received in revised form 18 April 2016
Accepted 22 April 2016

Keywords:
Triple point temperature
Single flash power plant
Steam-liquid separation process at separator
Available exergy function
Adiabatic heat drop at turbine

ABSTRACT

The USGS volumetric method is used for assessing the electrical capacity of a geothermal reservoir. The calculation formulas include both underground related parameters and above-ground related parameters. While primary variability and uncertainty in this method lay in the underground related parameters, electric capacity calculated is also a function of the above-ground related parameters. Among those parameters, the fluid temperature of the reservoir will be the key parameter for the volumetric method calculation when used with Monte Carlo method, because this temperature is the variable (uncertain) underground related parameter which affects the steam-liquid separation process in the separator – an above-ground related parameter. Conventional calculation methods do not deal with the steam-liquid separation process being affected by fluid temperature as a random variable when used together with Monte Carlo method. In order to fix up this issue, we have derived calculation formulas by introducing "Available Exergy Function", thereby, the fluid-temperature-dependant separation process can be included in the equations together with the fluid temperature as a random variable. This paper presents the electricity capacity calculations formulas that can be used for the volumetric method together with Monte Carlo method. In addition, a comparison is also made between the proposed method and the USGS method. The theoretical background of the proposed formula has eventually proved to be as same as the USGS method except for a few parameters adopted.

1. Introduction – issues of the calculation methods being available

The USGS (1978) defines the reservoir thermal energy available under a reference temperature by the following equation.

$$q_r = \rho CV\left(T_r - T_{ref}\right) \quad [\text{kJ}] \tag{1}$$

where q_r is geothermal energy that is stored in geothermal reservoir and is able to be used under a reference temperature condition, ρC is volumetric specific heat, V is reservoir volume, T_r is reservoir temperature and T_{ref} is reference temperature. It describes that the reference temperature (15 °C) is the mean annual surface temperature and for simplicity is assumed to be constant for the entire United States. A set of calculation equations are presented, on the basis of the second law of thermodynamics, to estimate electric energy to be converted from geothermal energy available under the reference temperature. Parameters required for the calculation of the electric generation capacity by using the USGS method are summarized in Table 1.

While primary variability and uncertainty in this method lay in the underground related parameters, considerations have also been directed to above-ground related parameters. The USGS method defines 'utilization factor' to convert heat energy to electric energy, giving 0.4 (USGS 1978). It was updated to 0.45 by USGS (2008). USGS (1978) states the given utilization factor is applicable only for the case that the reference temperature is 15 °C (the average ambient temperature in the United State) and the condenser temperature is 40 °C. On the other hand, Garg and Combs (2011) pointed out that the utilization factor depends on both power cycle and the reference temperature; the available work (calculated electric energy) is a strong function of the reference temperature. This suggests that type of power cycle has to be defined to obtain valid results when practicing the volumetric method.

We consider here a single flash condensing power cycle as a typical plant. Electric energy to be generated is calculated by well established conventional calculation processes for turbine-separator-condenser performance in accordance to thermodynamics; the electric energy generated is principally dependent on fluid temperature sent to separator together with

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http://dx.doi.org/10.1016/j.geothermics.2016.04.011

Table 1
Classification of parameters for USGS method (1978).

Underground related parameters	Above-ground related parameters
a-1. Reservoir volume: V [m^3]	b-1. Reference temperature: T_{ref} [°C]
a-2. Reservoir temperature: T_r [°C]	b-2. Utilization factor: η_u[−]
a-3. Volumetric specific heat: ρC [kJ/m^3 − K]	b-3. Plant life: L [sec]
a-4. Recovery factor: R$_g$ [−]	b-4. Plant factor: F [−]

Table 2
Proposed calculation equations for volumetric method.

Eq.-ID	Conditions				Electric Energy (kJ) Linear Approximation
	Separator		Condenser		
	P (bar-a)	T (°C)	P (bar-a)	T (°C)	
230	2	120.2	0.04	30	$(0.19 \pm 0.01)\ R_g \rho CV\ (T_r$-$120.2)$
240	2	120.2	0.07	40	$(0.17 \pm 0.01)\ R_g \rho CV\ (T_r$-$120.2)$
250	2	120.2	0.12	50	$(0.14 \pm 0.01)\ R_g \rho CV\ (T_r$-$120.2)$
260	2	120.2	0.20	60	$(0.11 \pm 0.01)\ R_g \rho CV\ (T_r$-$120.2)$
270	2	120.2	0.31	70	$(0.09 \pm 0.01)\ R_g \rho CV\ (T_r$-$120.2)$
330	3	133.5	0.04	30	$(0.23 \pm 0.01)\ R_g \rho CV\ (T_r$-$133.5)$
340	3	133.5	0.07	40	$(0.20 \pm 0.01)\ R_g \rho CV\ (T_r$-$133.5)$
350	3	133.5	0.12	50	$(0.17 \pm 0.01)\ R_g \rho CV\ (T_r$-$133.5)$
360	3	133.5	0.20	60	$(0.14 \pm 0.01)\ R_g \rho CV\ (T_r$-$133.5)$
370	3	133.5	0.31	70	$(0.12 \pm 0.01)\ R_g \rho CV(T_r$-$133.5)$
430	4	143.6	0.04	30	$(0.25 \pm 0.02)\ R_g \rho CV\ (T_r$-$143.6)$
440	4	143.6	0.07	40	$(0.22 \pm 0.01)\ R_g \rho CV\ (T_r$-$143.6)$
450	4	143.6	0.12	50	$(0.19 \pm 0.01)\ R_g \rho CV(T_r$-$143.6)$
460	4	143.6	0.20	60	$(0.17 \pm 0.01)\ R_g \rho CV\ (T_r$-$143.6)$
470	4	143.6	0.31	70	$(0.14 \pm 0.01)\ R_g \rho CV\ (T_r$-$143.6)$
530	5	151.8	0.04	30	$(0.27 \pm 0.02)\ R_g \rho CV\ (T_r$-$151.8)$
540	5	151.8	0.07	40	$(0.24 \pm 0.02)\ R_g \rho CV\ (T_r$-$151.8)$
550	5	151.8	0.12	50	$(0.21 \pm 0.01)\ R_g \rho CV\ (T_r$-$151.8)$
560	5	151.8	0.20	60	$(0.19 \pm 0.01)\ R_g \rho CV\ (T_r$-$151.8)$
570	5	151.8	0.31	70	$(0.16 \pm 0.01)\ R_g \rho CV\ (T_r$-$151.8)$
630	6	158.8	0.04	30	$(0.29 \pm 0.02)\ R_g \rho CV\ (T_r$-$158.8)$
640	6	158.8	0.07	40	$(0.26 \pm 0.02)\ R_g \rho CV\ (T_r$-$158.8)$
650	6	158.8	0.12	50	$(0.23 \pm 0.02)\ R_g \rho CV\ (T_r$-$158.8)$
660	6	158.8	0.20	60	$(0.20 \pm 0.01)\ R_g \rho CV\ (T_r$-$158.8)$
670	6	158.8	0.31	70	$(0.18 \pm 0.01)\ R_g \rho CV\ (T_r$-$158.8)$
730	7	165.0	0.04	30	$(0.31 \pm 0.02)\ R_g \rho CV\ (T_r$-$165.0)$
740	7	165.0	0.07	40	$(0.28 \pm 0.02)\ R_g \rho CV\ (T_r$-$165.0)$
750	7	165.0	0.12	50	$(0.25 \pm 0.02)\ R_g \rho CV\ (T_r$-$165.0)$
760	7	165.0	0.20	60	$(0.22 \pm 0.01)\ R_g \rho CV\ (T_r$-$165.0)$
770	7	165.0	0.31	70	$(0.19 \pm 0.01)\ R_g \rho CV\ (T_r$-$165.0)$
830	8	170.4	0.04	30	$(0.32 \pm 0.02)\ R_g \rho CV\ (T_r$-$170.4)$
840	8	170.4	0.07	40	$(0.29 \pm 0.02)\ R_g \rho CV\ (T_r$-$170.4)$
850	8	170.4	0.12	50	$(0.26 \pm 0.02)\ R_g \rho CV\ (T_r$-$170.4)$
860	8	170.4	0.20	60	$(0.23 \pm 0.02)\ R_g \rho CV\ (T_r$-$170.4)$
870	8	170.4	0.31	70	$(0.21 \pm 0.01)\ R_g \rho CV\ (T_r$-$170.4)$
930	9	175.4	0.04	30	$(0.34 \pm 0.02)\ R_g \rho CV\ (T_r$-$175.4)$
940	9	175.4	0.07	40	$(0.31 \pm 0.02)\ R_g \rho CV\ (T_r$-$175.4)$
950	9	175.4	0.12	50	$(0.28 \pm 0.02)\ R_g \rho CV\ (T_r$-$175.4)$
960	9	175.4	0.20	60	$(0.25 \pm 0.02)\ R_g \rho CV\ (T_r$-$175.4)$
970	9	175.4	0.31	70	$(0.22 \pm 0.01)\ R_g \rho CV\ (T_r$-$175.4)$
1030	10	179.9	0.04	30	$(0.35 \pm 0.02)\ R_g \rho CV\ (T_r$-$179.9)$
1040	10	179.9	0.07	40	$(0.32 \pm 0.02)\ R_g \rho CV\ (T_r$-$179.9)$
1050	10	179.9	0.12	50	$(0.29 \pm 0.02)\ R_g \rho CV\ (T_r$-$179.9)$
1060	10	179.9	0.20	60	$(0.26 \pm 0.02)\ R_g \rho CV\ (T_r$-$179.9)$
1070	10	179.9	0.31	70	$(0.23 \pm 0.01)\ R_g \rho CV\ (T_r$-$179.9)$

separator temperature and condenser temperature; a set of each fixed temperature may be given into the calculation process. However, these conventional calculation methods are not applicable when practicing the volumetric method together with Monte Carlo method because the fluid temperature shall be dealt as a random variable due to its uncertainty and the steam-liquid separation process is a fluid-temperature-dependant process. Calculation equations for the volumetric method need to satisfy those two requirements when used with Monte Carlo method. In order to provide this issue with a solution, we have derived calculation formulas by introducing "Available Exergy Function", thereby, fluid-temperature-dependant separation process can be included in an equation together with the fluid temperature as a random variable for the use with Monte Carlo method.

With the concept above, Takahashi and Yoshida (2015a) and Takahashi and Yoshida (2015b) proposed a simplified calculation formula, assuming a single flash condensing power cycle of the separator temperature 151.8 °C and condenser temperature 40 °C; the formula includes fluid temperature as a random variable and the function that reflects the fluid-temperature-dependant steam-liquid separation process; that can be used with Monte Carlo method. We herein refined the proposed method and expand its application to various combinations of separator and condenser temperatures assuming a single flash condensing power cycle.

Discussions on other important subjects of the underground related parameters are out of the scope of this paper. We believe the proposed equations will provide clearer ideas on the reservoir potential once the underground related parameters are properly defined.

2. Summary of the proposed calculation equations

The key points of the proposal are described below. A detailed explanation on how the equations have been derived are presented in Section 3 for verifications by readers.

a. We placed the "triple point temperature" in the Eq. (2) for the place of the reference temperature of the Eq. (1) of USGS (1978). The Eq. (2) represents the heat energy potentially stored in the geothermal reservoir, whereas the Eq. (1) defines the heat energy available in the reference temperature condition out of the heat energy potentially stored in a geothermal reservoir. This is because the fluid recovered at well head is sent to the power plant before exposed to any of reference conditions.

b. We adopted the concept of the "exergy" at a single flash condensing cycle by the Eq. (5) or Eq. (6) (adiabatic heat drop) in accordance to thermodynamics. This equation is eventually proved to be the same as the one given by USGS (1978) as the "Available Work" (Section 11).

c. We defined the "Available Exergy Function" by the Eq. (7). This represents the ratio of the exergy at a turbine-generation system against the total heat energy recovered at well head. Inclusion of the function in the calculation formula is the key idea of this paper.

d. By using the Available Exergy Function, the electricity to be generated is given by the Eq. (10). "Exergy efficiency", instead of "utilization factor", is included in the equation to tie up with the "exergy" adopted. This is the base equation from which approximation equations for application are derived.

e. For the separator temperature of 151.8 °C and the condenser temperature of 40 °C as an example; an approximation of the Available Exergy Function is given first as cubic polynomial as in the Eq. (21); this polynomial approximation is further simplified by the Eq. (23) for practical uses; Exergy efficiency is approximated in the Eq. (25), Eq. (26) based on 189 actual performance data; Electricity to be generated is given by the Eq. (27).

f. A comparison with USGS method is discussed in Sections 8 and 11 for further reference. A discussion on the utilization factor defined by USGS is also given in Section 11.

2.1. Application

We will first present the sets of equations in Table 2. Thereafter, the explanation is given on how those equations have been derived.

2.1.1. Underground related conditions

The underground related parameters listed in Table 1 shall be determined first. We referred to the USGS method (1978) for the