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Improvement of Calculating Formulas for Volumetric Resource Assessment

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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 USGS method except for a few parameters adopted.

Keywords: triple point temperature; single flash power plant; steam-liquid separation process at separator; available exergy function; adiabatic heat drop at turbine

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.

$$q_r = \rho C V (T_r - T_{ref}) \qquad \text{[kJ]} \qquad \text{(Eq. 1)}$$

Where q_r is geothermal energy that is stored in geothermal reservoir and is able to be used under reference temperature conditions, 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 ℃) 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 below.

Table 1 Classification of Parameters for USGS Method (1978)

A. Underground related parameters	**B.** Above-ground related parameters
a-1. Reservoir volume: V [m^3]	b-1. Reference temperature: T_{ref} [℃]
a-2. Reservoir temperature: T_r [℃]	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 [-]

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

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'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 ℃ (the average ambient temperature in the United State) and the condenser temperature is 40 ℃. On the other hand, S. K. Garg and J. 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 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 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 a equation together with the fluid temperature as a random variable for the use with Monte Carlo method. With the concept above, Takahashi and Yoshida (2015 a, 2015 b) proposed a simplified calculation formula, assuming a single flash condensing power cycle of the separator temperature 151.8 ℃ and condenser temperature 40 ℃; 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.

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 Chapter 3 for verifications by readers.

1. We placed the "triple point temperature" in the equation-2 for the place of the reference temperature of the equation-1 of USGS (1978). The equation-2 represents the heat energy potentially stored in the geothermal reservoir, whereas the equation-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.

2. We adopted the concept of the "exergy" at a single flash condensing cycle by the equation-5 or -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" (Chapter-11).

3. We defined the "Available Exergy Function" by the equation-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.

4. By using the Available Exergy Function, the electricity to be generated is given by the equation-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.

5. For the separator temperature of 151.8 ℃ and the condenser temperature of 40 ℃ as an example; an approximation of the Available Exergy Function is given first as cubic polynomial as in the equation-21; this polynomial approximation is further simplified by the equation-23 for practical uses; Exergy

efficiency is approximated in the equation-25, -26 based on 189 actual performance data; Electricity to be generated is given by the equation-27.

6. A comparison with USGS method is discussed in Chapter 8 and Chapter 11 for further reference. A discussion on the utilization factor defined by USGS is also given in Chapter-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 definitions and applications of those parameters. For the proposed calculation method, those parameters can be random variables for Monte Carlo method as has been practiced in the past. Much attention and examination shall be directed to the determination of those parameters because primary variability and uncertainty lay in the underground related parameters. Discussions on how to determine those parameters are out of scope of this paper.

2.1.2 Above-Ground Conditions for the Proposed Method

A single flash condensing system is assumed, where separator temperature and condenser temperature shall be pre-determined. The combination of separator temperature and the condenser temperature will be the index for selection of the simplified calculation equation presented in Table 2. Discussions on how to determine the separator temperature and the condenser temperature in relation to geothermal fluid characteristics are out of the scope of this paper. The following presentation however may be helpful.

Figure 1 shows the relative power output to be generated by a power plant with the separator pressures ranging from 2 bar-a to 10 bar-a, with two cases of condenser temperatures of T_{cd} =40℃ or T_{cd} =50℃, for the geothermal fluid temperature ranging from 200 ℃ to 350 ℃, (assuming $R_g \rho CV$=1 for the calculations of relative outputs). Power output may be maximum when the separator pressure of 5 or 6 bar-a for the fluid temperature of 250 ℃ - 275 ℃. These separator pressures may be recommended for an initial stage of resource evaluation if other conditions should allow to do so. Note that power output will be about 88 % when condenser temperature increases from 40 ℃ to 50 ℃ with the separator pressure of 5 bar-a just for a reference.

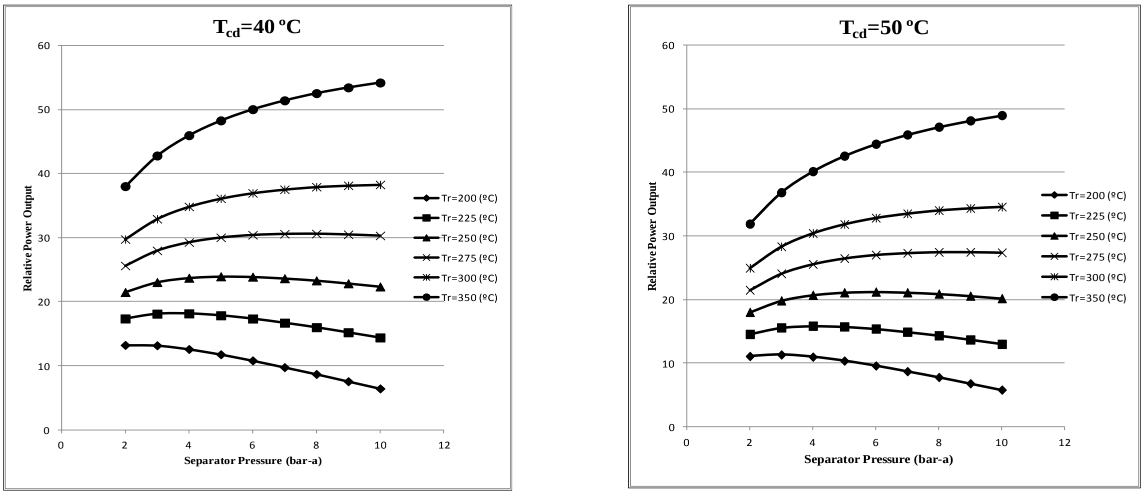

Figure 1: Relative Power Output for Various T_{sp} with T_{cd} =40 ℃ (Left) or T_{cd} =50 ℃ (Right)

2.1.3 A Note on “Reference Temperature” and “Utilization Factor”

For the proposed calculation method, we do not use such generalized temperature names as “reference temperature”, “abandonment temperature” or “rejection temperature”. Instead, specified temperatures as “triple point temperature”, “separator temperature” and “condenser temperature” are used to avoid possible misunderstandings. We do not use ‘utilization factor’ either, because it is originally defined for the use exclusively in the United State. It is a rather region specific factor. Instead of the “utilization factor”, we use plant specific “exergy efficiency” (defined by Equation-24) together with plant specific “exergy” (defined by Equation-5 or -6) at a turbine-generator. A brief observation on the “utilization factor” is given in Chapter 11.1 of this paper for further observation.

2.2 Calculation Equations

The sets of the calculation equations are presented in Table-2. Abbreviations appeared in the table are shown below.

E: Electric energy [kJ]
R_g : Recovery factor [-]
V: Reservoir volume [m^3]
T_r : Average reservoir temperature [℃]

$\rho C = (1-\varphi)C_r\rho_r + \varphi C_f\rho_f$: Reservoir volumetric specific heat [$\mathrm{kJ}/m^3 - \mathrm{K}$]
φ : Porosity [-]
C_r : Specific heat of rock [kJ/kg]
ρ_r : Rock density [kg/m^3]
C_f: Specific heat of fluid [kJ/kg]
ρ_f: Fluid density [kg/m^3]

A calculation equation is uniquely given by selecting a combination of the temperatures of the separator and the condenser. Numerical constants in the equations in Table-2 shall not be modified or changed in any case. These are the products from a series of approximation processes. Coefficients of the turbine-generator efficiency are included in the numerical terms in the equations based on information of actual power plants all over the world.

The average output capacity of the power plant in a designed plant life period is given as follows.

$$W_e = \mathrm{E}/(\mathrm{FL}) \qquad [kJ] \text{ or } [kW]$$

Where; “We” is the average output capacity of the power plant, “F” is the plant utilization factor, “L” is the plant life period.

Table 2 Proposed Calculation Equations for Volumetric Method[1]

Equ-ID	Conditions				Electric Eneergy (kJ) Linear Approximation (After Zero point Correction)
	Separator		Condenser		
	P (bar-a)	T (ºC)	P (bar-a)	T(ºC)	
430	4	143.6	0.04	30	(0.25 ± 0.02) * $Rg\rho CV$ * (Tr -143.6)
440	4	143.6	0.07	40	(0.22 ± 0.01) * $Rg\rho CV$ * (Tr -143.6)
450	4	143.6	0.12	50	(0.19 ± 0.01) * $Rg\rho CV$ * (Tr -143.6)
460	4	143.6	0.20	60	(0.17 ± 0.01) * $Rg\rho CV$ * (Tr -143.6)
470	4	143.6	0.31	70	(0.14 ± 0.01) * $Rg\rho CV$ * (Tr -143.6)
530	5	151.8	0.04	30	(0.27 ± 0.02) * $Rg\rho CV$ * (Tr -151.8)
540	5	151.8	0.07	40	(0.24 ± 0.02) * $Rg\rho CV$ * (Tr -151.8)
550	5	151.8	0.12	50	(0.21 ± 0.01) * $Rg\rho CV$ * (Tr -151.8)
560	5	151.8	0.20	60	(0.19 ± 0.01) * $Rg\rho CV$ * (Tr -151.8)
570	5	151.8	0.31	70	(0.16 ± 0.01) * $Rg\rho CV$ * (Tr -151.8)
630	6	158.8	0.04	30	(0.29 ± 0.02) * $Rg\rho CV$ * (Tr -158.8)
640	6	158.8	0.07	40	(0.26 ± 0.02) * $Rg\rho CV$ * (Tr -158.8)
650	6	158.8	0.12	50	(0.23 ± 0.02) * $Rg\rho CV$ * (Tr -158.8)
660	6	158.8	0.20	60	(0.20 ± 0.01) * $Rg\rho CV$ * (Tr -158.8)
670	6	158.8	0.31	70	(0.18 ± 0.01) * $Rg\rho CV$ * (Tr -158.8)
730	7	165.0	0.04	30	(0.31 ± 0.02) * $Rg\rho CV$ * (Tr -165.0)
740	7	165.0	0.07	40	(0.28 ± 0.02) * $Rg\rho CV$ * (Tr -165.0)
750	7	165.0	0.12	50	(0.25 ± 0.02) * $Rg\rho CV$ * (Tr -165.0)
760	7	165.0	0.20	60	(0.22 ± 0.01) * $Rg\rho CV$ * (Tr -165.0)
770	7	165.0	0.31	70	(0.19 ± 0.01) * $Rg\rho CV$ * (Tr -165.0)

3. DERIVING THE PROPOSED EQUATIONS

We will describe hereunder how the proposed calculation equations have been derived. The key abbreviations used correspond to those in Figure 2.

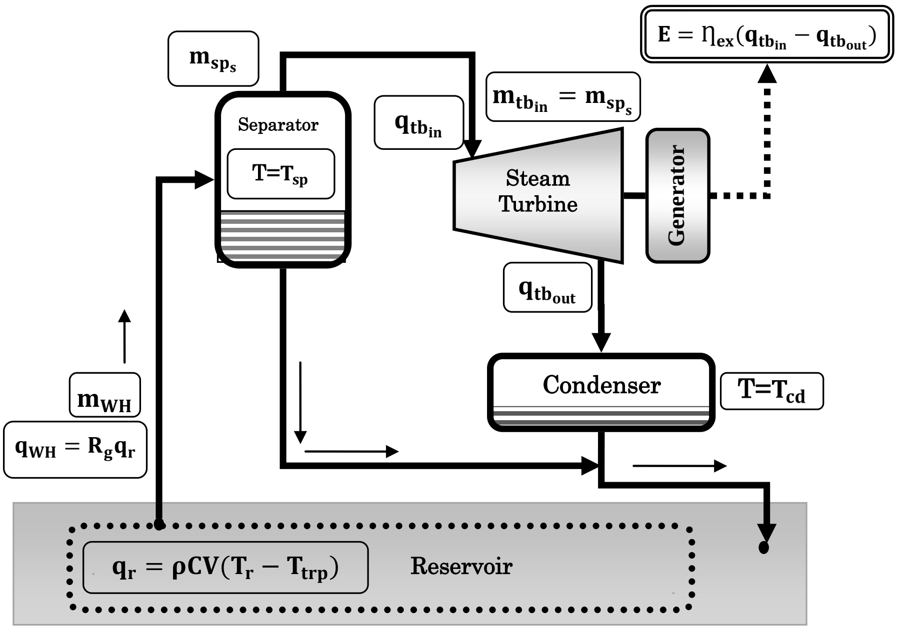

Figure 2 Simplified Single Flash Power Plant Schematic.

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[1] For the full table, please refer to: http://dx.doi.org/10.1016/j.geothermics.2016.04.011

3.1 Thermal Energy Potentially Stored in Geothermal Reservoir

The thermal energy potentially stored in a geothermal reservoir is given as follows.

Note that we placed T_{trp} (triple point temperature) in the equation Eq. 2 for the position of T_{ref} (reference temperature) of the equation Eq. 1 given by USGS (1978). The equation-2 represents the heat energy potentially stored in the geothermal reservoir, whereas the equation-1 defines the heat energy available in the reference temperature condition out of the heat energy potentially stored in a geothermal reservoir. The process of utilization of the geothermal fluid stored in a reservoir is made through three steps; (i) First, the geothermal fluid having the heat energy potentially stored in the reservoir is recovered at the well head (with recovery factor to be considered. See section 3.2); (ii) Second, the recovered fluid is sent into an energy utilization system before exposed to any of ambient conditions; (iii) Third, the heat energy, after utilized, decreases down to the final state condition. The equation Eq. 1 represents the heat energy made available through these three steps. Here, we consider the heat energy of the geothermal fluid at the first step only, where the fluid is not yet exposed to any of reference conditions such as the ambient temperature; the geothermal fluid retains potentially available heat energy at this step. In accordance to thermodynamics, potentially available heat energy of geothermal fluid of temperature $\boldsymbol{T_r}$ ºC is given by the equation Eq. 2 using the triple point temperature. The triple point temperature is the extreme minimum temperature for the reference temperature in thermodynamic. The potentially available heat energy is sent into the geothermal power plant.

3.2 Thermal Energy in the Reservoir, Recovery Factor

Since not all heat energy is recovered, the recovery factor is defined by USGS (1978) as follows.

$$\boldsymbol{R_g = q_{WH}/q_r} \qquad \textbf{[-]} \qquad \textbf{(Eq. 2)}$$

where R_g is the recovery factor, and q_{WH} is the heat energy recovered at the well head.

From the equations Eq. 2 and Eq. 3, the heat energy recovered at the well head is expressed by the following equation.

$$\boldsymbol{q_{WH} = R_g \rho C V (T_r - T_{trp})} \qquad \textbf{[kJ]} \qquad \textbf{(Eq. 3)}$$

This recovered heat energy is sent into separator through an adiabatic treated fluid transport pipe system without losing its energy to the ambient.

3.3 Electric Power Output from Turbine-generator

Electric power output generated by a steam turbine-generator system is expressed by the following equation using “adiabatic heat drop” between the heats at the turbine entrance and at the turbine exit (DiPippo 2008 or Hirata, et al 2008 or other references on thermodynamics).

$$\boldsymbol{E = \eta_{ex}\, m_{tb_{in}} (h_{tb_{in}} - h_{tb_{out}})} \qquad \textbf{[kJ]} \qquad \textbf{(Eq. 4)}$$

or

$$\boldsymbol{E = \eta_{ex} (q_{tb_{in}} - q_{tb_{out}})} \qquad \textbf{[kJ]} \qquad \textbf{(Eq. 5)}$$

Where η_{ex} is the turbine-generator efficiency (exergy efficiency), $m_{tb_{in}}$ is the mass of the steam at turbine entrance, $h_{tb_{in}}$ is the specific enthalpy at the turbine entrance, $h_{tb_{out}}$ is the specific enthalpy at the turbine exit, $q_{tb_{in}}$ is the thermal energy of the turbine entrance, $q_{tb_{out}}$ is the thermal energy of the turbine exit.

Note that the $h_{tb_{out}}$ is the heat energy at turbine exit under the condition when the heat at turbine entrance and heat at condenser (final state) are given, the explanation for this will be given in section 4.2.2; that the η_{ex} defined as the turbine-generator efficiency (exergy efficiency) is different from the 'utilization factor' defined by the USGS (1978). Also note that E defined by Eq. 5 is eventually proved to be the exergy energy (Available work) defined by USGS (1978) in Section 11 of the paper.

3.4 Definition of Available Exergy Function

We herein define the following equation. We name it "Available Exergy Function"

$$\zeta = (q_{tb_{in}} - q_{tb_{out}})/q_{WH} \qquad \textbf{[-]} \qquad \textbf{(Eq. 6)}$$

where; ζ is the Available Exergy Function

This is the ratio of the heat energy that contributes to electric power generation (i.e. exergy) at the turbine-generator against the whole thermal energy recovered at the well head.

3.5 Deriving the Rational Calculation Equation

We reform the equation Eq. 7 to the following equation.

$$(q_{tb_{in}} - q_{tb_{out}}) = \zeta\, q_{WH} \qquad \textbf{[kJ]} \qquad \textbf{(Eq. 7)}$$

Combination of the equation Eq. 6 and Eq. 8 gives the following equation.

$$E = \eta_{ex}\, \zeta\, q_{WH} \qquad \textbf{[kJ]} \qquad \textbf{(Eq. 8)}$$

Further, q_{WH} in the equation Eq. 9 is replaced with the equation Eq. 4, resulting in the following equation.

$$E = \eta_{ex}\, \zeta R_g\, \rho CV(T_r - T_{trp}) \qquad \textbf{[kJ]} \qquad \textbf{(Eq. 9)}$$

The equation Eq. 10 expresses the electric energy generated at a turbine-generator; the electric energy converted from the thermal energy sent into the turbine-generator of the efficiency η_{ex} (exergy efficiency).

4 CALCULATION OF THE AVAILABLE EXERGY FUNCTION

Although the equation Eq. 10 gives the electric energy to be converted from the thermal energy recovered at the well head, the equation is not ready for a practical calculation in field. This has to be expressed as an equation that shall be practically and user-friendlily used.

4.1 Assumptions

In order to convert the equation Eq. 10 to a calculable equation, we assume the following three conditions.

a. Geothermal fluid recovered at well head is assumed to have the enthalpy that corresponds to the enthalpy of the single phase liquid stored in the reservoir (as stated in 2.1),

b. Single flash condensing geothermal power plant is assumed for resource evaluation (as stated in 2.1),

c. Dry steam sent into the turbine and wet steam exhausted from the turbine is assumed.

4.2 Deriving the Calculable Equation of “Available Exergy Function ζ”

The Available Exergy Function consists of thermal energies (i) at the well head, (ii) at the turbine entrance and (iii) at the turbine exit. Calculation processes of these three thermal energies are explained hereunder step by step.

4.2.1 Geothermal energy recovered at the wellhead (q_{WH})

The geothermal energy at the well head is expressed by the following equation[2].

$$\boldsymbol{q_{WH_L} = m_{WH_L} h_{WH_L}} \qquad \textbf{[kJ]} \qquad \textbf{(Eq. 10)}$$

Where q_{WH_L} is the geothermal energy recovered at the wellhead, m_{WH_L} is the mass of the liquid recovered at the wellhead, h_{WH_L} is the specific enthalpy of the fluid recovered at the wellhead.

4.2.2 Thermal energy at turbine entrance ($q_{tb_{in}}$)

The geothermal fluid recovered at the well head is sent into the separator, separated into steam fraction and liquid fraction; and the steam fraction (dry steam) only is sent into the turbine. The thermal energy of the dry steam sent into the turbine is first given by the equation Eq. 12 and Eq. 13; the Equations Eq. 12 and Eq. 13 are re-written using water/steam separation ratio (Eq. 14), as the equation Eq. 15 below.

$$\boldsymbol{q_{tb_{in}} = m_{sp_s} h_{sp_s}} \qquad \textbf{[kJ]} \qquad \textbf{(Eq. 11)}$$

$$\boldsymbol{m_{sp_s} = \alpha_{sp_s} m_{WH_L}} \qquad \textbf{[kg]} \qquad \textbf{(Eq. 12)}$$

$$\boldsymbol{\alpha_{sp_s} = (h_{WH_L} - h_{sp_L})/(h_{sp_s} - h_{sp_L})} \qquad \textbf{[-]} \qquad \textbf{(Eq. 13)}$$

$$\boldsymbol{q_{tb_{in}} = \alpha_{sp_s} m_{WH_L} h_{sp_s}} \qquad \textbf{[kJ]} \qquad \textbf{(Eq. 14)}$$

Where $q_{tb_{in}}$ is the thermal energy sent into the turbine, m_{sp_s} is the mass of the steam fraction separated at the separator and sent into the turbine, h_{sp_s} is the specific enthalpy of the steam fraction separated at the separator and sent in to the turbine, α_{sp_s} is the ratio of the steam mass fraction separated at the separator, h_{sp_L} is the specific enthalpy of the liquid fraction separated at the separator.

4.2.3 Thermal energy at turbine exit ($q_{tb_{out}}$)

The dry steam sent into the turbine is losing its thermal energy being converted into electric energy. At the same time the dry steam is becoming to be wet steam. The thermal energy of the wet steam exhausted at the turbine exit is given in the following equation. Note the mass of the steam fraction at the turbine entrance is preserved at the turbine exit.

$$\boldsymbol{q_{tb_{out}} = m_{sp_s} h_{tb_{out_{SL}}}} \qquad \textbf{[kJ]} \qquad \textbf{(Eq. 15)}$$

Where $q_{tb_{out}}$ is the thermal energy at the turbine exit, $h_{tb_{out_{SL}}}$ is the specific enthalpy of the wet steam fraction at the turbine exit.

Dryness of the steam exhausted at the turbine exit is given by the following equation (DiPippo 2008 and/or Hirata et. al 2008).

$$\boldsymbol{\chi = (s_{sp_s} - s_{cd_L})/(s_{cd_s} - s_{cd_L})} \qquad \textbf{[-]} \qquad \textbf{(Eq. 16)}$$

Where χ is the quality of steam (dryness of steam), s_{sp_s} is the entropy of the steam at the separator, s_{cd_L} is the entropy of the liquid at the condenser and s_{cd_s} is the entropy of the steam at the condenser. Using the

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[2] Note that the equation $m_{WH} = q_{WH}/(h_{WH} - h_{ref})$ given by USGS(1978) is valid only when $h_{ref} = 0$.

equation E. 17, the specific enthalpy of the wet steam fraction exhausted at the turbine exit is given by the following equation.

$$\boldsymbol{h_{tb_{out_{SL}}} = h_{cd_L} + (h_{cd_s} - h_{cd_L})\chi}$$ **[kJ/kg]** **(Eq. 17)**

Where h_{cd_L} is the specific enthalpy of the liquid at the condenser and h_{cd_s} is the specific enthalpy of the steam at the condenser.

Combination of the equations Eq. 16, Eq. 17 and Eq. 18 gives the following equation.

$$\boldsymbol{q_{tb_{out}} = \alpha_{sp_s} m_{WH_L} h_{tb_{out_{SL}}}}$$ **[kJ]** **(Eq. 18)**

4.2.4 The Available Exergy Function (ζ)

Replacing the terms in the equation Eq. 7 (Available Exergy Function) with the equations Eq. 11, Eq. 15 and Eq. 19 gives the following equation.

$$\boldsymbol{\zeta = \alpha_{sp_s}(h_{sp_s} - h_{tb_{out_{SL}}})/h_{WH_L}}$$ **[-]** **(Eq. 19)**

An approximation equation of the Available Exergy Function will be derived by the equation Eq. 20 through specifying the combination of a separator temperature and a condenser temperature.

5 APPROXIMATION EQUATION (AN EXAMPLE) OF AVAILABLE EXERGY FUNCTION

5.1 Step One Approximation to Cubic Polynomial

In order to convert “Available Exergy Function” into a calculable equation, a set of a separator temperature and a condenser temperature has to be selected first. There are a number of combinations of the temperatures; among those one sample approximation equation is derived assuming a typical temperature combination.

a. Separator temperature : 151.8℃ (0.5 MPa)

b. Condenser temperature : 40.0℃ (0.007 MPa)

The correlation between the geothermal fluid temperature and the Available Exergy Function is presented in Figure 3 for this example. Figure 3 shows that the thermal energy contributing to electricity power generation in the turbine ranges from 8% to 16 % for the geothermal fluid temperature ranging from 200 ℃ to 300 ℃.

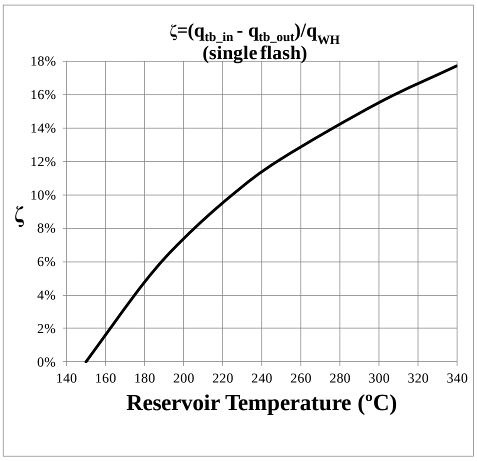

Figure 3 Available Exergy Ratio vs. Fluid Temperature
(for T_{sp}=151.8 ℃, T_{cd}=40.0 ℃)

The approximation equation of the correlation is given by the following cubic polynomial.

$$\boldsymbol{\zeta = 0.0000000127\ T_r^3 - 0.0000124900\ T_r^2 + 0.0046543806 T_r - 0.4591082158} \qquad \textbf{(Eq. 20)}$$

Note that the Available Exergy Function shall be zero ($\zeta = 0$) when the fluid temperature equals to the separator temperature according to the definition of the equation (see Eq. 7). For this example of the separator temperature T_{sp}=151.8 ℃ , ζ shall theoretically be zero ($\zeta = 0$). (However, this is not necessarily attained by the approximation although we specified ten digits after the decimal point for the coefficients.)

5.2 Step Two Appropriation to a Practical Equation for the Available Exergy Function

The equation Eq.21 as an approximation equation of the Available Exergy Function, is still somewhat too large to be used as a user-friendly calculation equation. Thus, a simpler and more user-friendly approximation equation is hereunder derived.

There is a lenear correlation between $\zeta(T_r - T_{trp})$ in the equation Eq. 10 on the vertical axis and $(T_r - T_{sp})$ on the horizontal axis. Since when $T_r = T_{sp}$, $\zeta = 0$, the correlation between $\zeta(T_r - T_{trp})$ and $(T_r - T_{sp})$ is expressed by the following equation.

$$\boldsymbol{\zeta(T_r - T_{trp}) = A(T_r - T_{sp})} \qquad \textbf{[-]} \qquad \textbf{(Eq. 21)}$$

Where A is a constant.

For this example of T_{sp}= 151.8 ℃ and T_{cd} =40 ℃ the equation Eq. 22 shall be as follows.

$$\boldsymbol{\zeta(T_r - T_{trp}) = 0.3155(T_r - 151.8)} \qquad \textbf{[-]} \qquad \textbf{(Eq. 22)}$$

(For T_{sp}= 151.8 ℃ and T_{cd}=40 ℃ only)

6 TURBINE-GENERATOR EFFICIENCY (η_{ex})

The equation Eq. 5 defines the electric energy converted from the thermal energy, using the adiabatic heat-drop concept at a turbine. The equation includes the turbine-generator efficiency (exergy efficiency). The equation Eq. 5 is reformed to the following equation.

$$\boldsymbol{\eta_{ex} = E/\{m_{tb_{in}}(h_{tb_{in}} - h_{tb_{out}})\}} \qquad \textbf{[-]} \qquad \textbf{(Eq. 23)}$$

We analyzed the correlation between turbine-generator efficiencies (η_{ex}), and temperature drops ($T_{tb_{in}} - T_{cd}$) of turbine entrance and condenser. We used 189 data of geothermal power plants all over the world (listed in ENAA 2013 in Japanese) resulting in the following correlation (Figure 4).

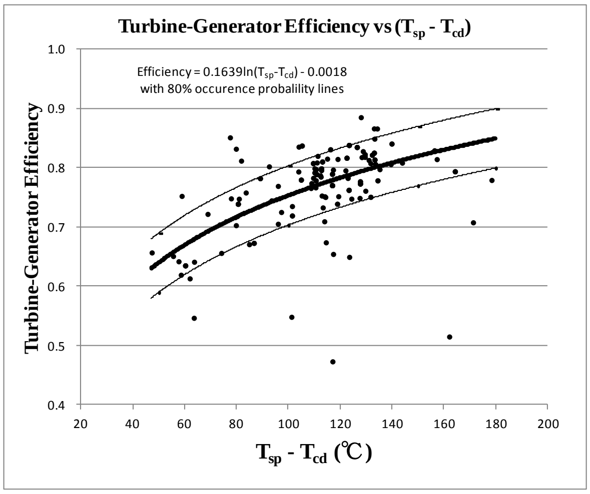

Figure 4 Turbine-Generator Efficiency from 189 data

$$\boldsymbol{\eta_{ex} = 0.164\ \ln\left(T_{tb_{in}} - T_{cd}\right) - 0.002 \pm 0.05} \qquad \textbf{[-]} \qquad \textbf{(Eq. 24)}$$

Where; $\mathbf{T_{tb_{in}}}$is the temperature of the turbine entrance and T_{cd} is the temperature of the condenser.

The actual efficiency of a turbine-generator system depends on many factors that include the efficiency of basic power plant design, resource temperature, concentrations of dissolved gases in the reservoir fluid, the condition of plant maintenance and so on. For this reason, we included a range of ± 0.05 in the approximation equation Eq. 25, which encompasses 153 data among the 189 data (approximately 80% occurrence probability).

For this example of T_{sp}= 151.8 ℃ and T_{cd}=40 ℃, the equation Eq. 25 is as follows.

$$\boldsymbol{\eta_{ex} = 0.77 \pm 0.05} \qquad \textbf{[-]} \qquad \textbf{(Eq. 25)}$$

(For the case of T_{sp}= 151.8 ℃ and T_{cd}=40 ℃ only)

7. A RATIONAL, PRACTICAL AND USER-FRIENDLY EQUATION FOR VOLUMETRIC METHOD

7.1 Approximation for the Example of T_{sp}= 151.8 ℃ and T_{cd}=40 ℃

Replacing $\zeta(T_r - T_{trp})$ and η_{ex} in the equation Eq. 10 with the equations Eq. 23 and Eq. 26 gives the following equation.

$$\mathbf{E = (0.24 \pm 0.02) R_g \rho C V (T_r - 151.8)} \qquad \textbf{[kJ]} \qquad \textbf{(Eq. 26)}$$

(For the case of T_{sp}= 151.8 ℃ and T_{cd}=40 ℃ only)

The equation Eq. 27 above gives the electric energy converted in the geothermal power plant with separator of T_{sp}= 151.8 ℃ and condenser of T_{cd}=40 ℃. The other factors, i.e. recovery factor (R_g), Volumetric specific heat of the reservoir (ρC), reservoir volume (V) and average reservoir temperature (T_r) have to be given by the practitioners in charge.

7.2 Approximation Equations for Various Sets of Separator Temperatures and Condenser Temperatures

We have derived approximation equations for various sets of separator temperatures and condenser temperatures, so that practitioners may select one or some of those that may suite to their site conditions. The equations are presented in Table-2.

8. NOTES AND DISCUSSIONS

It has been pointed out that the USGS method may have given larger resource estimations than that of reservoir resources actually available on site. Thus, the proposed method may also give excessive resource estimation than actual. In connection with this issue, one may be tempted to calibrate the equations by changing the constants in the equations of the proposed method. However, any of the constants shall not be changed, because the equations in Table-2 do not represent any of thermodynamic implications directly; the separator temperature in the second brackets acts only for zero-point adjustment; the constants in the first brackets are only the resultants of the approximations.

If the calculation results should not agree to the reservoir resource actually available, such reservoir related factors have to be reviewed as recovery factor (R_g), volumetric specific heat of the reservoir (ρC), reservoir volume (V) and average reservoir temperature (T_r). In particular, recovery factor (R_g) and reservoir volume (V) shall have to be examined prudently, because the two factors will give significant impacts on the resource assessment.

9. CONCLUSIONS

The USGS method is widely used for assessing the electrical capacity of a geothermal reservoir. While the under-ground related parameters will have significant impacts on the resource assessment, the electric capacity calculated is a strong function of the above-ground related conditions. The fluid temperature recovered at well head 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. We have derived calculation formulas by introducing “Available Exergy Function”, thereby, fluid-temperature-dependant separation process can be included in the equations together with the fluid temperature as a random variable for the Monte Carlo method. It is expected that this calculation method may provide clearer ideas on geothermal resources assessment because the above-ground related parameters are separately defined from the much uncertain underground related parameters. The proposed calculation formulas are proved to be on the same theoretical base of the USGS method (1978). They may thus give larger resource estimation than actually monitored on site if conventional underground related parameters should be selected. However, any of coefficients in the equations of the proposed method must not be changed or adjusted or calibrated. It is the underground related factors that shall be reviewed. In particular, recovery factor and/or reservoir volume have to be reviewed.

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