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Steam and Water Relative Permeabilities Calculation Using Production Test Data and Tortuous Channel Model Modified Equations

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ABSTRACT

The steam and water relative permeabilities of a well at Momotombo geothermal reservoir have been attempted to calculate using available production test data. Flowing saturation value (S_{wf}) it yields by means the reservoir steam fraction obtained from flowing enthalpy production test and bottomhole temperature recorded; both values have been used to determine fluids properties, then S_{wf} will be used to determine the local water saturation value (S_w) by means of the relationship derived by Chen (2005) in fractured porous media, after that it will be used together with relative water saturation and immobile nucleated steam saturation values (S_{wr}, S_{gn}) determined by means trial and error in order to get relative permeabilities using steam relative permeability equation proposed by Chen (2005) and water relative permeability equation proposed in this work, then is possible to calculate the effective viscosity to match the flowing enthalpy from production test data. These preliminary relative permeabilities data could be used for initial modelling reservoir purposes, to determine the potential energy available and help to define possible technology to use.

1. INTRODUCTION

Fluid flows in geothermal systems usually occurs through the interstices of surrounding rocks, considering two phase flows only steam and water; the flow of each phase is affected by the interaction between these two phases water and steam, as well as by the thermodynamic effects of boiling heat transfer, in that way several researches have been developed in order to determine how these two phases interact.

The objective of this work was to develop a method to calculate the relative permeabilities of steam and water by using flowing enthalpy of each stabilized step during the production test and the downhole temperature recorded to determine fluid properties that are utilized then for calculating the steam fraction at downhole condition. The relative permeabilities cannot be determined directly because the water saturation is normally not known for the reservoirs, relationships between the flowing water saturation and in place water saturation determined by Chen (2005) have been utilized to calculate water saturation in order to determine the steam relative permeability of the reservoir fluid by means Modified Tortuous Channel Model (MTCM) equations proposed by Chen (2005) and water relative permeability equation proposed in this work, in that way it is not necessary the long-term production data as required by Shinohara method (1978).

2. THEORITICAL BACKGROUND

2.1 Production test data utilization.

Initially the bottomhole temperature available will be used to calculate steam and water properties at reservoir condition and the flowing enthalpy will be used to calculate the reservoir steam fraction.

In real geothermal situation, it is difficult to determine the local water saturation. Nevertheless, the flowing saturation ($S_{w,f}$) can be determined using Eq. (1), (Reyes, 2004).

$$S_{w,f} = \frac{(1-x)v_w}{(1-x)v_w + xv_s} \tag{1}$$

Where v_w and v_s are the specific volumes of water and steam respectively at reservoir condition.

Steam fraction (x) is defined in Eq. (2).

$$x = \frac{h_f - h_w}{h_s - h_w} \tag{2}$$

Where $\boldsymbol{h_f}$ is the flowing enthalpy from the production test and $\boldsymbol{h_w}$ and $\boldsymbol{h_s}$ are the water and steam enthalpy respectively determined in this work by means Tortike correlation (1989) using the available recorded bottomhole temperature at the end of production test which could be obtained from dynamic recorder during production test, static recorder after production test or geothermometers.

2.2 Relationships determined from laboratory results by Chen (2005).

From the laboratory data obtained by Chen (2005) at 104°C, the water saturation S_w and the flowing water saturation $S_{w,f}$ were both known and the following expressions were determined for different roughness surfaces

SM $S_w = 0.1152\ln(S_{w,f}) + 0.8588$ (3)

HR $S_w = 0.0431\ln(S_{w,f}) + 0.6592$ (4)

RR $S_w = 0.073\ln(S_{w,f}) + 0.7974$ (5)

2.3 Water and Steam Relative Permeabilities determination.

The water and steam relative permeabilities can be determined by means equations (6) and (7) proposed by Chen (2005) in his Modified Tortuous Channel Model equations (MTCM) that can describe the steam-water relative permeabilities from smooth rough (SM), homogeneously rough (HR) and randomly rough (RR) fractures and also the earlier results from consolidated Berea sandstone [Satik, 1998] and unconsolidated sand [Verma, 1986]. In the present work the original equation for water relative permeability proposed by Chen (Eq. 6) has been modified, gotten a better matching result with data from Satik (1998) and data from Verma (1986), see Fig. 1.

$$k_{rw} = (1 - S_{gn})(0.74S_w^{*2} + 0.26S_w^*) \quad (6)$$

$$k_{rs} = 0.43S_g^{*3} + 0.38S_g^{*2} + 0.19S_g^* \quad (7)$$

Where k_{rw} and k_{rs} are steam and water relative permeabilities respectively and S_{gn} is the immobile nucleated steam saturation.

The following expression is the modified water relative permeability equation proposed in this work.

$$k_{rw} = (1 - S_{gn})^{1.0801} * S_w^{0.4002} * (0.74S_w^{*2} + 0.26S_w^*) \quad (8)$$

S_w^* is the normalized water saturation defined as:

$$S_w^* = \frac{S_w - S_{wr}}{1 - S_{wr}} \quad (9)$$

S_g^* is the normalized steam saturation defined as:

$$S_g^* = \frac{1 - S_w - S_{gn}}{1 - S_{wr} - S_{gn}} \quad (10)$$

S_w is the water saturation, and S_{wr} is the relative water saturation.

Water relative saturation (S_{wr}) and the immobile nucleated steam saturation S_{gn} values will be determined by trial and error until to match the flowing enthalpy from Production test data.

2.4 Flowing Enthalpy calculation.

Steam and water relative permeabilities values gotten before will be used for calculating the effective viscosity (ν_t) and the flowing enthalpy (h_f) by the Equations (11) and (12) (G.S. Bodvarsson et al., 1980).

$$\frac{1}{\nu_t} = \frac{k_{rw}}{\nu_w} + \frac{k_{rs}}{\nu_s} \quad (11)$$

$$h_f = \nu_t\left(h_w\frac{k_{rw}}{\nu_w} + h_s\frac{k_{rs}}{\nu_s}\right) \quad (12)$$

Where h_f is the flowing enthalpy, ν_t is the effective kinematic viscosity, ν_w and ν_s are the water and steam kinematic viscosities respectively.

2.5 Relative Permeabilities curve comparison MCTM (Chen, 2005) equations and proposed $\boldsymbol{k_{rw}}$ equation.

In order to compare the proposed $\boldsymbol{k_{rw}}$ equation with the MCTM equation, they have been plotted the Chen (2005) data together with the permeability curves (Fig 1), black lines represent MCTM (Chen, 2005) equation and the dashed red line represents the proposed $\boldsymbol{k_{rw}}$ equation, in the homogeneously rough (HR) and randomly rough (RR) fracture cases the dashed red line fit the data better than de $\boldsymbol{k_{rw}}$ equation from Chen (2005).

Table 1 shows statistical comparison results between original MTCM equations (Chen, 2005) and the proposed k_{rw} equation in this work, in the homogeneously rough (HR) and randomly rough (RR) fracture cases, Means Absolute Error (MAE) using the proposed equation are less than the MAE results from original MCTM equations; similarly in both cases the correlation index are greater using proposed k_{rw} equation than using the original MTCM equations. In the RR case, data inside the ellipse was not considered for the statistical analysis.

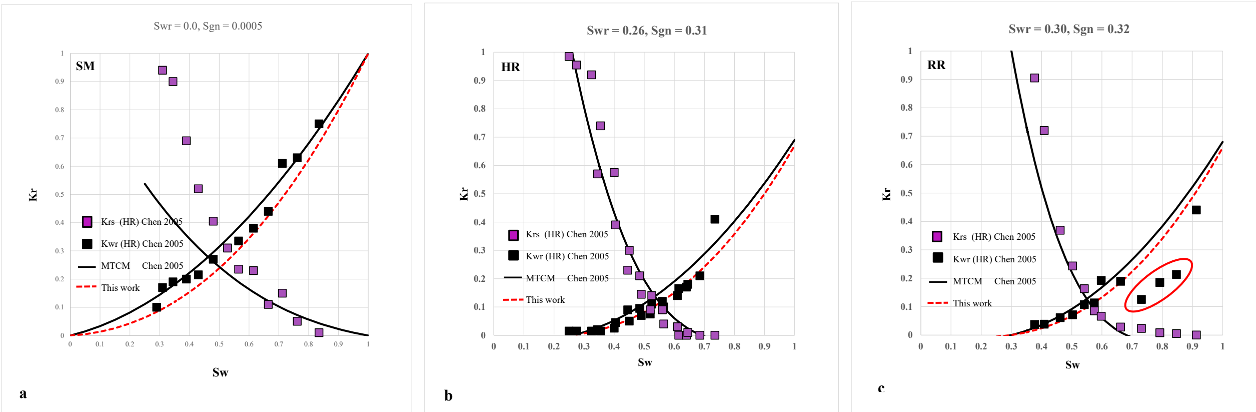

Figure 1: Steam water relative permeabilities curves comparison using MTCM and Modified water equation proposed in this work: a) smooth rough fracture (SM) b) Homogeneously rough fracture (HR), c) and randomly rough fracture (RR).

Table 1: Statical Comparison of fitting performance and corresponding optimal fitting parameters between MTCM (Chen, 2005) and MTCM with Krw modified equation.

Chen data, 2005	MTCM Chen (2005)				This work			
	Swr	Sgr	MAE	R^2	Swr	Sgr	MAE	R^2
Smooth Fracture	0.0000	0.0005	0.0316	0.9629	0.0000	0.0005	0.0516	0.9050
HR fracture	0.2600	0.3100	0.0353	0.7882	0.2600	0.3100	0.0179	0.8658
RR fracture	0.3000	0.3200	0.0708	0.9109	0.3000	0.3200	0.0549	0.9368

2.6 Relative Permeabilities curve comparison using previous researches results.

Figure 2 shows the fitting results of water relative permeability in Berea sandstone (Satik, 1998), and unconsolidated sand (Verma, 1986) using MTCM equations (6) and (7) (black line), and Modified water relative permeability equation (8) proposed in this work (dashed red line), in both cases the equation proposed fits closer than equation (6) to the measured water relative permeability data. Table 1 shows statistical comparison results between original MTCM equations (Chen, 2005) and the proposed k_{rw} equation in this work, in both cases Means Absolute Error (MAE) from results using the proposed equation are less than the MAE results from original MCTM equations; similarly in both cases the correlation index are greater using proposed k_{rw} equation than using the original MTCM equations.

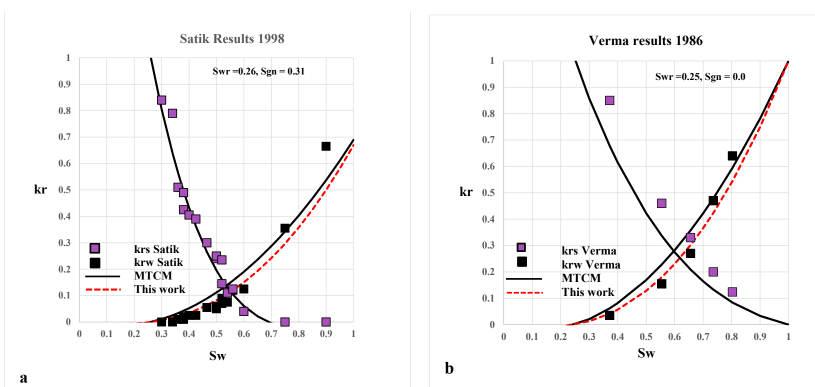

Figure 2: Steam water relative permeabilities curves comparison using MTCM and Modified water equation proposed in this work: a) Berea sandstone data from Satik (1998), b) Unconsolidated sand data from Verma (1986).

Table No. 2: Statical comparison of fitting performance and corresponding optimal fitting parameters between MTCM (Chen, 2005) and MTCM with Krw modified equation.

Preliminary works	MTCM Chen (2005)				This work			
	Swr	Sgr	MAE	R^2	Swr	Sgr	MAE	R^2
Berea Sandstone (Satik, 1998)	0.2600	0.3100	0.0463	0.8981	0.2600	0.3100	0.0294	0.9157
Unconsolidated sand (Verma, 1986)	0.3300	0.0000	0.0486	0.9324	0.2500	0.0000	0.0412	0.9447

3. FIELD STUDY. MOMOTOMBO GEOTHERMAL FIELD, NICARAGUA.

Momotombo Geothermal field is located 40 km northwest of Managua city Nicaragua, on the northwestern shore of Managua Lake at the foot of Momotombo volcano, it rises an altitude of 1297 masl, which forms part of the Cordillera de los Maribios, a chain of active volcanoes extending along Nicaragua Pacific Coast (Figure 3). Since 1975, forty-seven wells have been drilled in the Momotombo field, ranging in depth from 310 to 2839 m. At the present 11 wells are in production to the power plant and seven wells, mostly in the eastern part of the field are been used for reinjection.

In 1983 was commissioned the First Unit of 35 MW, later in 1988 was commissioned the Second Unit of 35 MW. In July 1999, Ormat started to manage the Momotombo geothermal field as a result of an international bid signed a 15 years concession and power purchase agreement, Porras (2009). At date 2022 a private company Momotombo Geothermal Power (MPC) has an exploitation concession by 15 years.

Figure 3. Location Momotombo Geothermal field. (After Martinez et al.; 1988).

Structurally the geothermal field is characterized mainly by three fault systems running NW-SE, NE-SW and N-S (Figure 4). Regional faults are aligned in a N-S direction; Momotombo fault and SR fault are the principal NW-SE faults and Bjornsson's fault is the main NE-SW fault, these faults allow the fluids circulation in the hydrothermal system (Porras, 2009).

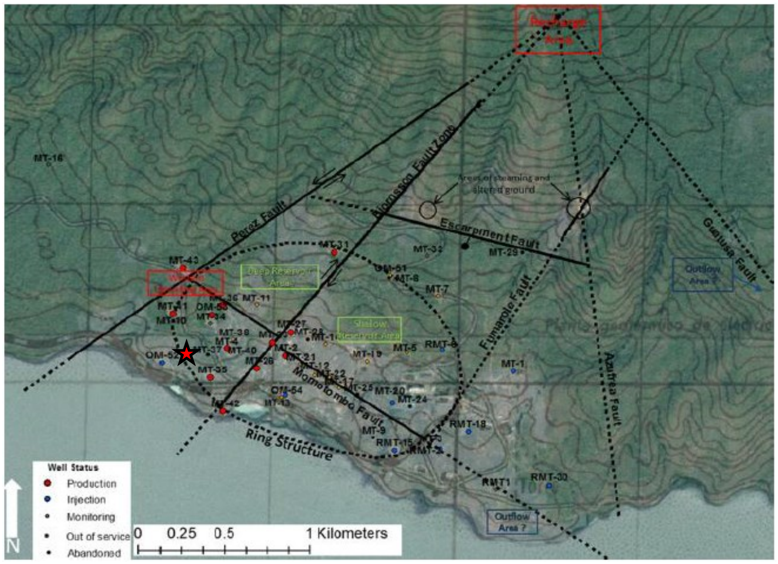

Figure 4. Momotombo geothermal field map showing wellhead location, postulated faults and likely zones of recharge upwelling and outflow (Kaspereit D. et al, 2016). MT-35 ★

The revised conceptual model of Momotombo geothermal system assumes that recharge area originates beneath the steaming ground mapped at an elevation of above 500 masl and the hydraulic gradient transport fluids to the current field along the Perez and Bjornsson's faults (Kaspereit D. et al, 2016).

The high temperature fluid up flow is located in western part of the field. There the hot fluids move through West Momotombo fault and rises through Bjornsson's fault toward the shallow aquifer through the East Momotombo and SR faults.

At day the electrical generation is 26 MW, 20 MW from single flashing unit and 6 MW from binary bottoming cycle unit.

3.1 Production test MT -35.

MT-35 Production test was carried out from January 12 until February 23 1988 (DAL, 1988), before the commissioning of Unit II of Momotombo Geothermal Field, the procedure used was flow after flow without any shut in well between flow rate changes. The first discharge stage was at full open condition, after 160 hours this was stopped due to a short circuit in the Unit I electrical transmission line, it was not possible to get the stabilization flow for this stage; after that the test continued at different rates increasing the wellhead pressure (shutting master valve), but the discharge times were not uniform.

The bottomhole temperature recorder at the beginning of Production test was 309.71 °C, at the end of Production test, the bottomhole temperature recorded was 296.01°C. this value has been used to determine the properties fluid using correlation equations (Tortike, 1989), that have been used to calculate relative permeabilities.

The production test results at atmospheric condition are shown in Table No. 3.

Momotombo Geothermal Field
Production test results MT-35

Table No. 3

Date	Time	Discharge time	WHP	Water	Wt	H	Xr
		hours	Barg	T/h	T/h	Kj/Kg	Eq.(3)
19/1/1988	08:27	174.5	10.70	62.646	214.87	2017.6	0.4816
29/1/1988	13:46	192	20.70	58.836	187.07	1990.0	0.4624
2/2/1988	10:50	69	25.00	60.299	185.73	1943.1	0.4298
4/2/1988	11:05	48	29.00	60.299	176.73	1905.8	0.4039
8/2/1988	10:45	95.75	34.50	64.469	168.81	1853.5	0.3675
11/2/1988	10:59	72.25	40.70	60.299	151.56	1778.1	0.3150
16/2/1988	10:25	119.5	46.10	57.983	129.84	1668.0	0.2385
1/3/1988	10:06	172	49.80	40.58	99.82	1542.4	0.1511

3.2 Steam water relative permeabilities calculation using Modified tortuous channel model (MTCM) equations

In the present work it has been used the equations (3), (4) and (5) to determine S_w [Chen, 2005], S_{wr} and S_{gn} will be determine by trial and error in order to get the steam and water relative permeabilities and matching the Flowing enthalpy values from MT-35 Production test data. Figure 5, shows the relative permeabilities curves for each fracture media that have been considered.

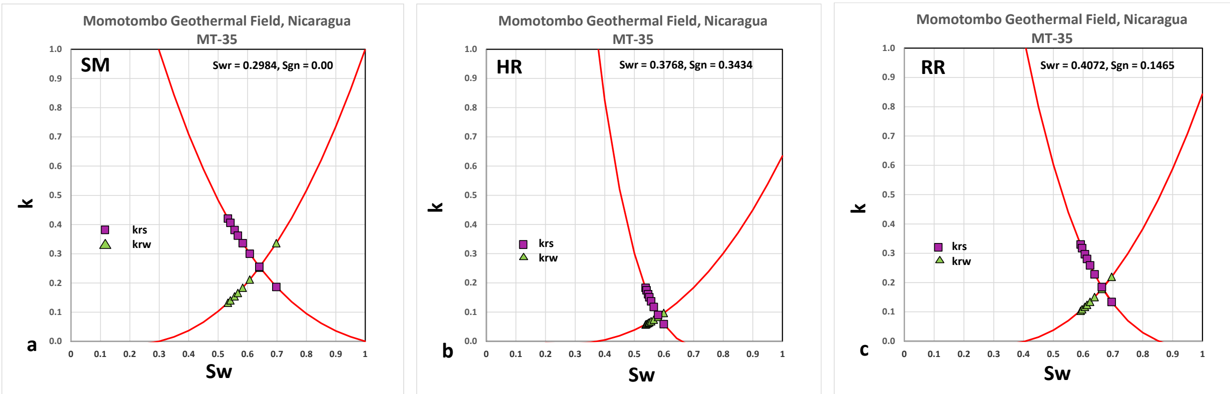

Figure 5. Comparison of steam water relative permeabilities curves from MTCM equations in a) Smooth Rough (SM), b) Homogeneous Rough (HR) and c) Randomly Rough fractures (RR).

Table No. 4 shows the results for Smooth Rough Fracture case, S_w values were determined by means Eq. (3), S_{wr} and S_{gn} values selected were 0.2984 and 0.00 respectively, only the maximum enthalpy value from the production test data was matched, the rest of enthalpy calculated were less than enthalpy from production test data.

Momotombo Geothermal Field, MT-35, (SM)
Relative permeabilities, Smooth Fracture , Swr=0.2984, Sgn=0

Table No. 4

WHP	Swf	Sw	S*w	S*g	Krw	Krs	hf (Kj/Kg)
Barg	Eq. (1)	Eq. (3)	Eq. (9)	Eq. (10)	Eq. (8)	Eq. (7)	Eq. (12)
10.70	0.0594	0.5335	0.3351	0.6649	0.1324	0.4207	2017.58
20.70	0.0638	0.5418	0.3470	0.6530	0.1403	0.4059	1983.85
25.00	0.0722	0.5560	0.3672	0.6328	0.1544	0.3814	1928.05
29.00	0.0797	0.5674	0.3834	0.6166	0.1661	0.3625	1885.01
34.50	0.0917	0.5836	0.4065	0.5935	0.1837	0.3366	1826.53
40.70	0.1131	0.6077	0.4409	0.5591	0.2118	0.3002	1746.37
46.10	0.1578	0.6400	0.4869	0.5131	0.2526	0.2556	1653.35
49.80	0.2478	0.6981	0.5697	0.4303	0.3363	0.1864	1525.59

Table No. 5 shows the results for Homogeneous rough Fracture case, S_w values were determined by means Eq. (4), S_{wr} value selected was 0.3768, S_{gn} value selected was 0.3434, enthalpy value calculated are in good agreement with the production test data.

Momotombo Geothermal Field, MT-35, (HR)
Relative permeabilities, Homogeneous rough Fracture, Swr=0.3768, Sgn=0.3434

Table No. 5

WHP	Swf	Sw	S*w	S*g	Krw	Krs	hf (Kj/Kg)
Barg	Eq. (1)	Eq. (4)	Eq. (9)	Eq. (10)	Eq. (8)	Eq. (7)	Eq. (12)
10.70	0.0594	0.5375	0.2579	0.4257	0.0576	0.1829	2017.49
20.70	0.0638	0.5406	0.2629	0.4145	0.0593	0.1747	1990.37
25.00	0.0722	0.5459	0.2714	0.3956	0.0623	0.1612	1944.31
29.00	0.0797	0.5502	0.2782	0.3804	0.0648	0.1509	1907.64
34.50	0.0917	0.5562	0.2879	0.3587	0.0684	0.1369	1855.99
40.70	0.1131	0.5653	0.3024	0.3264	0.0739	0.1175	1781.19
46.10	0.1578	0.5796	0.3254	0.2752	0.0832	0.0900	1670.66
49.80	0.2478	0.5991	0.3567	0.2056	0.0966	0.0589	1542.41

Table No. 6 shows the results for Randomly rough Fracture case, S_w value was determined by means Eq. (5), S_{wr} value selected was 0.4073 and S_{gn} value was 0.1459 the maximum and minimum enthalpy values from the production test data were matched, the calculated intermedial values are in agreement with the flowing enthalpy from the production test data.

Momotombo Geothermal Field, MT-35 (RR)

Relative permeabilities, Randomly rough Fracture , Swr=0.4072, Sgn=0.1465

Table No. 6

WHP	Swf	Sw	S*w	S*g	Krw	Krs	hf (Kj/Kg)
Barg	Eq. (1)	Eq. (5)	Eq. (9)	Eq. (10)	Eq. (8)	Eq. (7)	Eq. (12)
10.70	0.0594	0.5913	0.3105	0.5876	0.1039	0.3301	2017.57
20.70	0.0638	0.5966	0.3194	0.5757	0.1087	0.3174	1987.36
25.00	0.0722	0.6055	0.3346	0.5556	0.1171	0.2966	1936.86
29.00	0.0797	0.6127	0.3467	0.5395	0.1241	0.2806	1897.39
34.50	0.0917	0.6230	0.3640	0.5165	0.1344	0.2587	1842.95
40.70	0.1131	0.6383	0.3898	0.4822	0.1506	0.2282	1766.55
46.10	0.1578	0.6626	0.4308	0.4278	0.1782	0.1845	1659.08
49.80	0.2478	0.6956	0.4865	0.3539	0.2198	0.1339	1542.43

The best enthalpy results were obtained using the HR fracture case.

3.3 Flowing enthalpy comparison.

Flowing enthalpy calculations were determined by means equations (11) and (12), using the relative permeabilities gotten previously and compared with the Flowing enthalpy from the production test.

Table No. 7 shows the summary enthalpy results from the three cases considered, Homogeneous rough fracture case result shows the best approach with the minimal MAE of 1.4687, Smooth rough fracture case shows a higher MAE with a value of 16.5313.

Momotombo Geothermal Field, MT-35

Comparison of enthalpy calculated and Enthalpy from production test data

Table No. 7

WHP	Prod test	SM	HR	RR	ABSOLUTE ERROR		
Barg	hf	hf	hf	hf			
	Kj/Kg	Kj/Kg	Kj/Kg	Kj/Kg	SM	HR	RR
10.70	2017.62	2017.58	2017.49	2017.57	0.0390	0.1302	0.0534
20.70	1989.99	1983.85	1990.37	1987.36	6.1349	0.3851	2.6217
25.00	1943.09	1928.05	1944.31	1936.86	15.0468	1.2181	6.2344
29.00	1905.83	1885.01	1907.64	1897.39	20.8221	1.8131	8.4390
34.50	1853.50	1826.53	1855.99	1842.95	26.9620	2.4973	10.5480
40.70	1778.13	1746.37	1781.19	1766.55	31.7610	3.0532	11.5854
46.10	1668.02	1653.35	1670.66	1659.08	14.6742	2.6384	8.9422
49.80	1542.40	1525.59	1542.41	1542.43	16.8102	0.0144	0.0333
			Mean Absolute Error		16.5313	1.4687	6.0572

Enthalpy results were plotted in Figure 6 showing that the best fitting was obtained by the homogeneous rough fracture case (dark orange triangle) in according with the minimal MAE obtained.

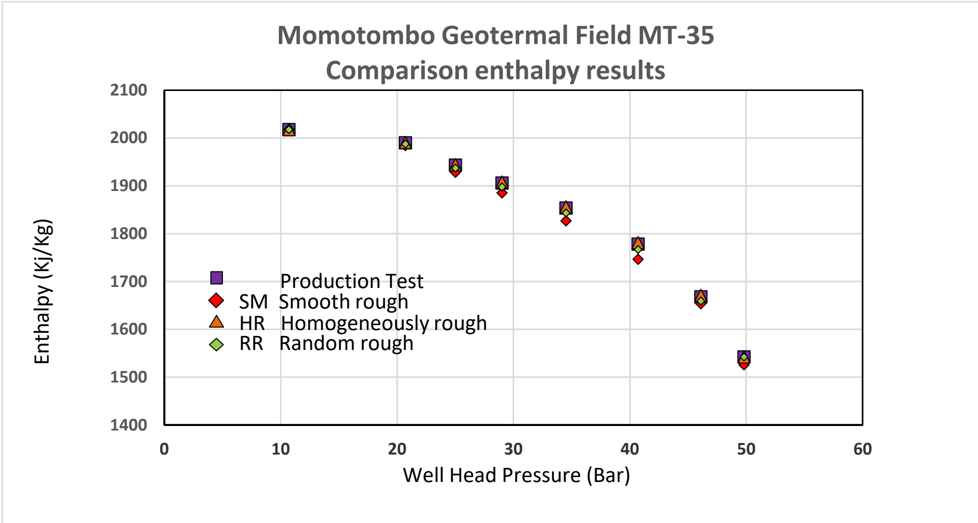

Figure 6. Flowing Enthalpy results comparison.

4. CONCLUTIONS AND RECOMENDATIONS

A new procedure has been presented to calculate water and steam relative permeabilities using Modified Tortuous Channel Model (MTCM) equations and production test data.

A modified water relative permeability equation has been proposed, the water relative permeability curves obtained are in excellent agreement with previous results from different authors.

This procedure can use all early data from production test and not require a long-term data such as Shinohara method.

With this procedure is possible to get at early time relative permeabilities values to be use in preliminary modeling purposes determining the potential energy available and choices the possible technology to use.

S_{wr} and S_{gn} values obtained by means S_w relationship for homogeneous rough fracture case for MT-35 were 0.3768 and 0.3434 respectively, also enthalpy flowing shows an excellent agreement with the Production Test data with a MAE value of 1.4687.

It is necessary to take in account that the values obtained are representative of the feed zone of the well in study and not for the reservoir due to the heterogeneity of the reservoir.

It is recommended to realize additional academic research at higher temperature in order to improve S_w and $S_{w,f}$ relationship; the equations utilized in the present work were obtained at 104°C (Chen,2005), considering for this reason that the procedure proposed is not definitive yet.

It is recommended to check the permeabilities values obtained in laboratory with the values obtained by this procedure in other fields where these data are available, taking in account that geothermal field is heterogeneous and will show different values around the field.

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