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Evaluation of Well NWS-6D's Potential as Energy Resource for 5 MWe Sabalan Pilot Power Plant Project

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ABSTRACT

The Sabalan geothermal field is a high-temperature area under development. Geothermal exploration was started in 1975 by the Ministry of Energy of Iran. After revolution in 1979 in Iran, it was stopped, and it was started again in 1998 by SUNA – the Renewable Energy Organization of Iran. Three deep exploration wells and two shallow reinjection wells were drilled in 2002-2004 in three sites A, B and C, by SUNA beside the preparation of two sites D and E for new drilling. This area is about 16 km southeast of the town of Meshkinshahr. There is an overall potential for the generation of about 200 MWe over the greater prospect area. SKM (main consultants 1998-2006) assessed that commercial geothermal power generation could be achieved at Sabalan at a levelized cost of electricity of less than 5 USc/kWh. SUNA is planning to drill thirteen new wells, and build a 50 MWe power plant, when these wells will be drilled. As the first part of project, SUNA will build a pilot power plant in order to confirm that a geothermal power plant can be operated in Iran. Moshanir was the consultant for civil work during 1998-2006 and since 2006 the consortium of Moshanir, EDC and Lahmeyer was selected as the main consultant for geothermal field. New drilling was started since 2008 and continued until 2011. In this period 5 deep wells were drilled and one of the pervious wells was deeper.

Well NWS-6D was the sixth well drilled in the second phase of exploration and the third to be discharged. This well was flow tested in the time period from 7th January to 31th May in 2011. Test apparatus included a full flow atmospheric silencer associated with required piping, valves & fittings and instruments. A weir provided in the bottom of silencer was used for measuring separated brine water flow. According to the test results at six steps corresponding to six throttle valve (installed in well outlet) positions well head pressure (WHP), pH and chloride content of brine water remained constant to record water flow and lip pressure (pressure of entering fluid to the silencer) to be applied for the calculation of total mass flow (TMF) and enthalpy of outlet fluid from the well.

1. INTRODUCTION

Iran is situated in the Middle East and has area of 1,648,195 km^2 with a population of about 75 million. It has big gas and oil reservoirs and also it is one of the world´s main oil producers. There are ample potentials of renewable energies in Iran, such as solar, biomass, wind and geothermal.

The geothermal activity in Iran started by the Ministry of Energy of Iran (MOEI) in 1975, a contract between MOEI and Ente Nazionale per L' Energia Electtrica of Italy (ENEL) was signed for geothermal exploration in the northern part of Iran (Azerbaijan and Damavand regions). In 1993 SUNA were established to justify priorities of the above mentioned regions. As a result, Meshkinshar and Sarein areas in Sabalan region were proposed for electric and direct use respectively (Figure 1). In 1998 SKM on behalf of SUNA completed a resistivity survey consisting of Direct current (D.C.), Transient electromagnetic (TEM) Magnetotellurics (MT) measurements in Meshkinshahr.

A variety of power generation development options have been formulated and assessed, with generation capacities ranging from 2 to 100 MWe, utilizing both condensing and non condensing steam turbines by SKM (SKM, 2005).

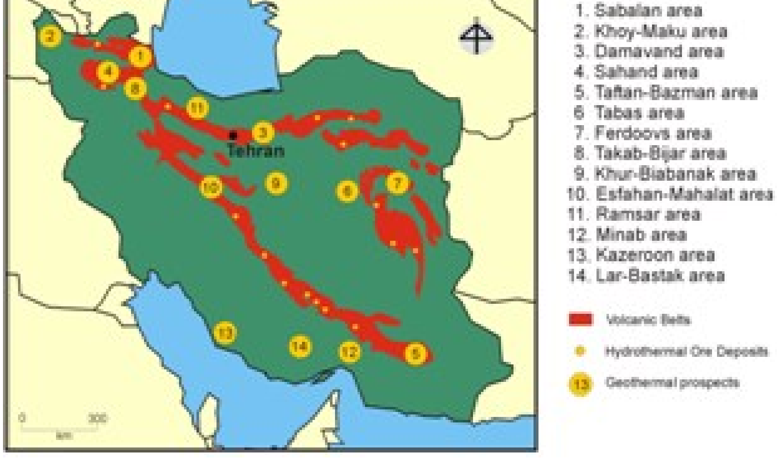

Figure 1: Map of IRAN (SKM, 2005)

The Mt. Sabalan geothermal field is located in the Moil Valley on the northwest flank of Mt. Sabalan, close to the Meshkinshahr town (Khiyav) of Azerbaijan, Iran. The field is located between 38° 11' 55" and 38° 22' 00" North and 47° 38' 30" and 47° 48' 20"

(Yousefi, 2004). The resource area has been previously identified by geo-scientific studies as an approximately quadrangular shaped area that covers approximately 75 km^2.

Access to the area is provided by a sealed road from the nearby town of Meshkinshahr to the village of Moil, then to the valley south of the village by an unsealed road. A sealed road connects the Meshkinshahr to the provincial capital city of Ardebil.

The geothermal field is located in an environmentally sensitive area of elevated valley terraces set within the outer caldera rim of the greater Mt. Sabalan complex. Vegetation is limited to light scrub and pasture with some smallholdings and associated arable planting (SKM, 2005). Mt. Sabalan is a Quaternary volcanic complex that rises to a height of 4811 m, some 3800 m above the Ahar Chai valley to the north. Volcanism within the Sabalan caldera has formed three major volcanic peaks which rise to elevations of around 4700 m.

The climate in the area is relatively dry, especially during the summer months. The site is exposed to severe winter weather, including very high wind speeds of up to 180 km/hr. Temperatures over the past 4 years have been measured as low as - 30°C (SKM, 2005).

After the geological exploration phase, the project was divided into two-phases; the first phase (1998-2006) was aiming to build drilling pads at sites A, B, C, including excavation and construction concrete pad, (Figure 2), accesses roads from Moil village to sites, a pump station, water reservoir, water intake and water pipelines from pump station to reservoir and all sites. This phase includes also to repair the existing road between Meshkinshahr and Moil village and to drill five exploratory wells. In the second phase, SUNA has decided to build a 5 MWe pilot power plant on site B for observing the actual viability of a geothermal power plant in Iran and simultaneously drill 14 production or reinjection wells, including preparations of well pads A and B, for additional drilling, and well pads D and E, for new drilling. This phase includes also the accesses road to site E, water pipeline and new pump station in order to provide water for drilling on site E. After deepening the 5th well and drilling 6 new wells in this phase, drilling operations were shut down because of lack of budget, now SUNA is planning to build a 5 MWe power plant in order to reach generating electricity.

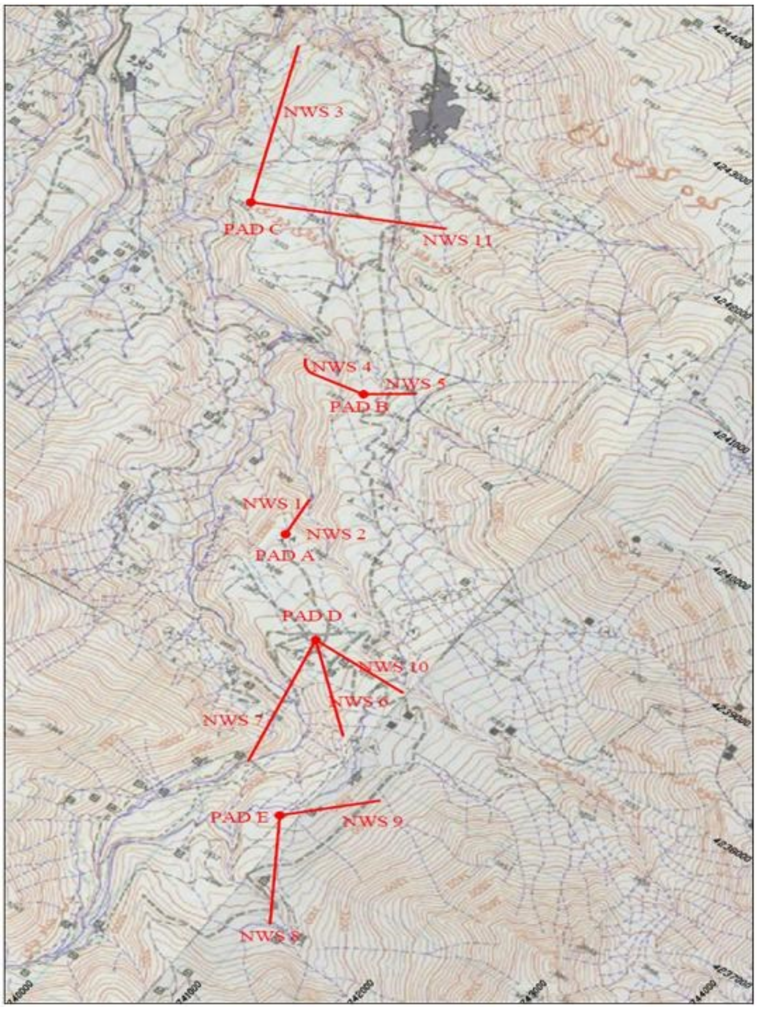

Figure 2: Plan of Sabalan area

In this paper, the above 5 MWe power plant is assumed in near site D, with steam from production well NWS-6D.

The main objective of this study was the potential evaluation of well NWS-6D in different well head pressures and different separator pressures that we could generate the largest capacity.

2. EXPLORATION OF SABALAN GEOTHERMAL AREA

2.1 Exploration Drilling Program (first phase)

In this phase the drilling and testing program was carried out between November 2002 and December 2004. The three deep exploration wells which were drilled are coded to as NWS-1, NWS-3 and NWS-4 on well pads A, C and B, respectively. The wells vary in depth from 2265 to 3197 m MD. Well NWS-1 was drilled vertically while NWS-3 and NWS-4 are deviated wells with throws of 1503 and 818 m, respectively. Additionally, two shallow reinjection wells have been drilled to 600 m depth, NWS2R, located on pad A alongside well NWS-1, and NWS-5R on pad B alongside well NWS-4. The basic well completion data are summarized in Table 1.

2.2 Well Testing and Reservoir Results (first phase)

Well NWS-1 was discharged in May 2004 for a period of 21 days with reinjection of waste brine into shallow well NWS-2R. And well NWS-4 was discharged by airlift stimulation in September 2004 and was flow tested for the next four months with reinjection of waste brine into shallow well NWS-5R. Output curves for well NWS-1 and well NWS-4 are shown in Figure 3. These show variations in total mass and enthalpy with flowing wellhead pressure. Both wells discharged with enthalpies in the range of 950-1000 kJ/kg, which is consistent with production from liquid-only feed zones with temperatures of 230°C (for NWS-1) and 220°C (for NW-4). These are both lower than the maximum temperatures measured in the two wells of 245 and 230°C, respectively.

Shallow well NWS-2R Output curves for well NWS-1 and well NWS-4 are shown in Figure 3. These show variations in total mass and enthalpy with flowing wellhead pressure. Both wells discharged with enthalpies in the range of 950-1000 kJ/kg, which is consistent with production from liquid-only feed zones with temperatures of 230°C (for NWS-1) and 220°C (for NW-4). These are both lower than the maximum temperatures measured in the two wells of 245 and 230°C, respectively.

Table 1: Basic completion information of NWS wells (SKM, 2005)

Well	Spud date	Completion date	Depth (mMD / mVD)	Product. casing		Product. liner	
				Size (in)	Depth (mMD)	Size (in)	Depth (mMD)
NWS-1	22 Nov 02	1 Jun 03	3197	9⅝	1586	7	3197
NWS-3	2 Jul 03	27 Nov 03	3166 / 2603	13⅜	1589	9⅝	3160
NWS-4	17 Dec 03	27 Mar 04	2255 / 1980	9⅝	1166	7	2255
NWS-2R	7 Jun 03	25 Jun 03	638	13⅜	360	9⅝, 5	638
NWS-5R	7 Apr 04	2 May 04	538	20	139	9⅝	482

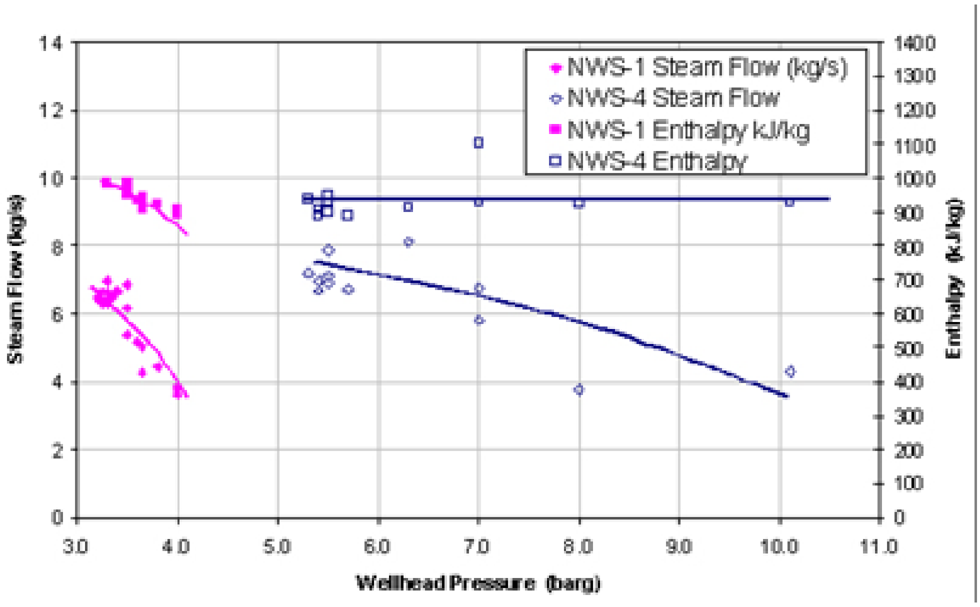

Figure 3: Output curve for wells NWS-1 & NWS-4 (SKM, 2004)

2.2 Delineation Drilling Program (second phase)

In this phase the drilling and testing program was carried out between May 2008 and October 2012.

The well NWS-5R was deepened to 1901 m and The five deep Delineation wells and one reinjection well which were drilled are coded as NWS-5D, NWS-6D, NWS-7D, NWS-8D, NWS-9D, NWS-10D and NWS-11R on well pads D, E, B and C, respectively. The wells vary in depth from 1901 to 2813 m MD. All of wells were drilled directionally. The basic well completion data are summarized in Table 2.

2.2 Well Testing and Reservoir Results (second phase)

Well NWS-6D was discharged by airlift stimulation in Jan 2011 for a period of 146 days with reinjection of waste brine into shallow well NWS-2R. And well NWS7-D was discharged by two-phase flow from well NWS6-D in June 2011 for a period of 82 days with reinjection of waste brine into shallow well NWS-2R. And well NWS10-D was discharged by two-phase flow from well NWS7-D in Aug 2011 for a period of 135 days with reinjection of waste brine into shallow well NWS-2R. And well NWS5-D was discharged by airlift stimulation in Sep 2012 for a period of 5 days with reinjection of waste brine into shallow well NWS-4. Well NWS9-D was discharged by airlift stimulation in Sep 2012 for a period of 76 days with reinjection of waste brine into Well NWS-2R. Well NWS-6D which we want to discuss about it, is the sixth drilled well in the second phase of drilling and third to be discharged. The injection well for this process was NWS2-R and it was 110 m lower than NWS6-D therefore the brine flow and injection to this well were implemented by gravity. Test apparatus included a full flow atmospheric silencer associated with required piping, valves & fittings and instruments. A weir box provided in the bottom of silencer, which it was used for measuring of separated brine water flow, the brine water transfer with a channel to cuttings pit and transfer with a 6 inch pipeline to NWS2-R. According to test results at five steps corresponding to five throttle valve (installed in well outlet pipeline) positions well head pressure (WHP), pH and chloride content of brine water remained constant according to water flow record and lip pressure (pressure of entering fluid to the silencer) which were applied for calculation of total mass flow (TMF) and Enthalpy of outlet fluid from the well. We used a webre separator in order to getting some steam samples. The result of test is shown in Figure 4 and Figure 5. There are some scattering in the enthalpy of these five results, it may be related to well behavior.

Table 2: Basic completion information of NWS wells

Well	Spud date	Completion date	Depth (mMD / mVD)	Product. casing		Product. liner	
				Size (in)	Depth (mMD)	Size (in)	Depth (mMD)
NWS-5D	May-30-2008	Aug-31-2008	1901	9⅝	745	7	1901
NWS-6D	Oct-16-2008	Feb-19-2009	2377	9⅝	1250	7	2371
NWS-7D	Mar-26-2009	Aug-17-2009	2705	9⅝	1313	7	2705
NWS-8D	Aug-21-2009	Jan-21-2010	2640	9⅝	1438	7	2640
NWS-9D	Feb-08-2010	Mar-19-2010	500	9⅝	-	7	-
NWS-10D	Apr-10-2010	Sep-o5-2010	2300	9⅝	977	7	-
Re-NWS-9D	Sep-16-2010	Dec-16-2010	2703	9⅝	1101	7	2703
NWS-11R	Dec-25-2010	May-10-2010	2813	9⅝	1286	7	2813

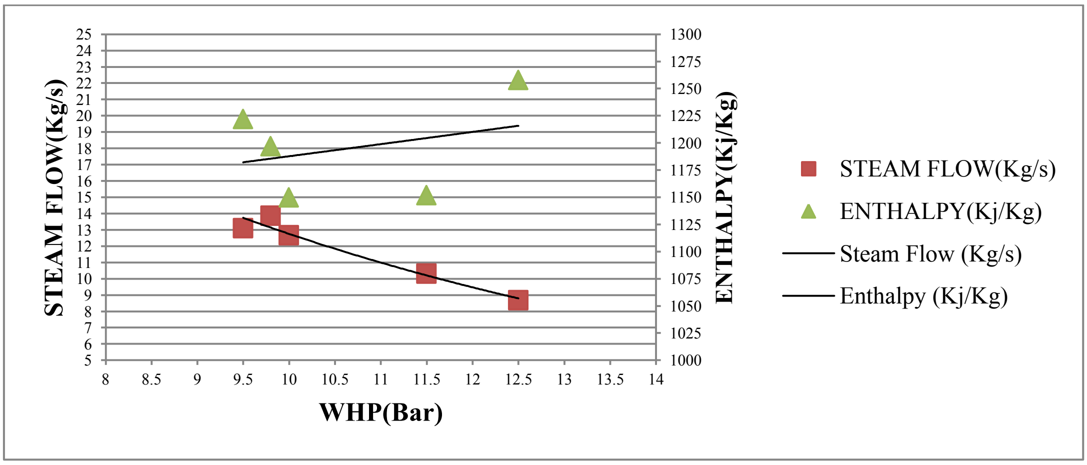

Figure 4: Stem flow output curve for well NWS-6D

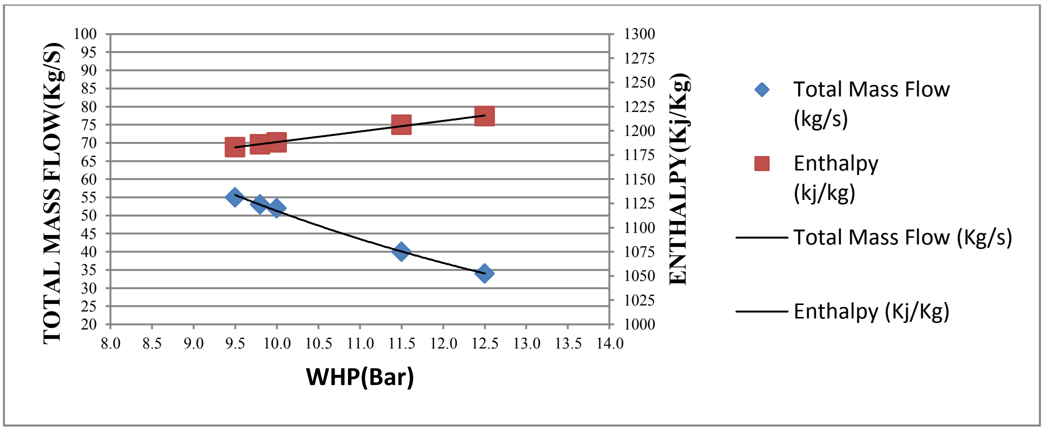

Figure 5: Total mass flow output curve for wells NWS-6D

3. THEORY AND METHOD OVERVIEW OF CALCULATIONG WELL POTENTIAL

In this part we discuss about thermodynamic design aspects of various power cycles involving power production from geothermal wells. The power cycles that are used in geothermal are as fallow:

- A single flash steam power cycle using the geothermal fluid as a working fluid.
- A double flash steam power cycle.
- Power cycles where geothermal and working fluids are separated.
- An organic Rankine cycle with different working fluids for the power cycle.
- The Kalina power cycle.

In order to analyze a power cycles, the function of various plant components are described in sufficient detail for a single flash steam power cycle. The focus here will be on the general function with respect to the thermodynamics as well as their efficiency for conceptual design of a single flash power cycle.

3.1 Theory background

3.1.1 Fluid properties

In order to analyze a power cycle based on a specific working fluid, the thermodynamic properties of the fluid must be known. These properties involve

Pressure p , given in Pa, kPa or bar.

Temperature T , given in °C or K

Enthalpy h , which is measurement of energy contents of a unit mass flow of fluid. A frequently used unit for enthalpy is kj/kg.

Entropy s , given in kj/(kg.K). The change in entropy will be zero if generating process or work absorption is without exchanging heat with the environment.

Specific volume v , in m^3/kg. It is rarely used but can be used for calculating flow speed based on pipe diameters and mass flow.

The working fluid is in most cases in gas form, liquid form or a mixture of gas and liquid. As an example, the enthalpy of saturated liquid would be denoted by h_l and the enthalpy for saturated steam as h_g .

The properties of mixtures are given as follows

$$h_l = (1-x)h_l + xh_g \quad (1)$$

$$s = (1-x)s_l + xs_g \quad (2)$$

$$v = (1-x)v_l + xv_g \quad (3)$$

Where x is the mass fraction of the gas phase with respect to the mass of the mixture (Pálsson, 2007).

3.1.2 Thermodynamic processes

Four basic processes are considered when analyzing geothermal power plants, which are as follow:

- Isentropic process, where the entropy s is constant. This involves expansion in turbines as well as compressors and pumps. In this case, work is delivered or consumed ideally with no losses to the environment or fluid.

- Isenthalpic process, where the enthalpy h is constant. In such a process, no work or heat is delivered or consumed from the environment and therefore the energy contents of the fluid remains constant. An example is expansion in a throttling valve.
- Isobaric process, where the pressure p is constant. This is an ideal assumption as before and is appropriate where almost no pressure changes take place in a process.
- Heat exchange, where heat but not work is transferred to or from the fluid. This involves change in both enthalpy and entropy, but in most cases the pressure is constant.

The processes listed above will be used to calculate the changes in various fluid properties when the fluid flows through the different plant components (Pálsson, 2007).

3.1.2 Balancing equations

There are two types of balances that must be fulfilled for each component at all times.

The first one is mass balance for a steady system which is not changing in time. This requires that the sum of all mass flow $\dot{m}$, given in kg/s, into a component must be equal to the mass flow out of the component.
The second one is an energy balance requirement. This states that the sum of energy flow into a component must be equal to the energy flow out of it. The flow of energy can take three forms, namely

- Energy of the flowing fluid, denoted by $\dot{m}h$
- Work performed or consumed, W.
- Heat flowing into or from a component, Q.

3.2 Plant components

3.2.1 The well

The geothermal well is the starting point for a thermodynamic analysis of a steam power cycle. Generally, three properties characterize a geothermal well are as follow:

- The wellhead pressure, p_w, which is the pressure at the top of the well. We assume that we can reduce this pressure by using a throttling valve at the well top.

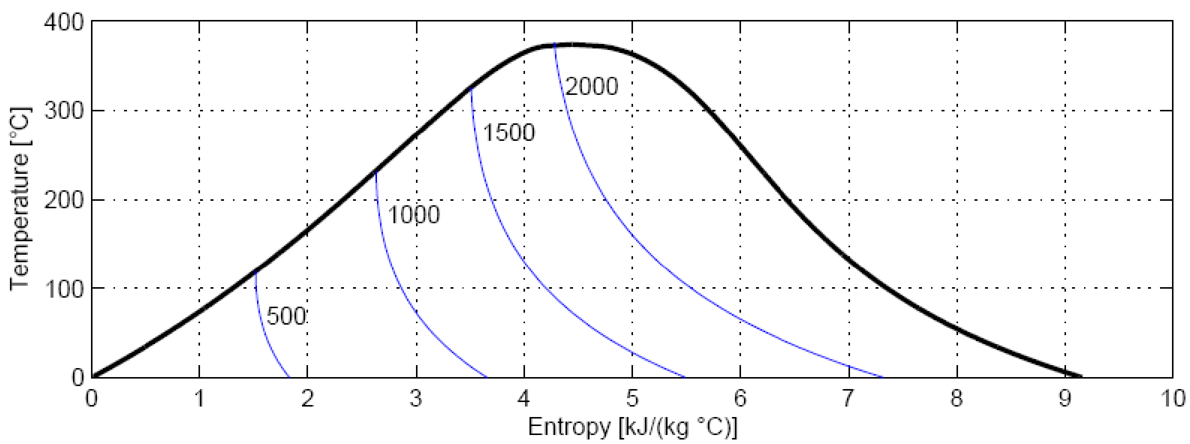

Figure 6: Constant enthalpy lines on a $T-s$ diagram (Pálsson, 2007).

- The mass flow from the well, $\dot{m}$, which is also related to the wellhead pressure. The mass flow is highly dependent on the properties of the geothermal area deep down in the well.
- The saturation temperature of water, T_0, at the bottom of the well. This value is related to the expected energy contents per kilogram of fluid flowing from the well.

The well temperature T_0 can be used to calculate the specific enthalpy of the well, h_0 which is simply the saturation enthalpy of water at temperature of T_0.

It can be assumed with enough accuracy that the enthalpy of the fluid flowing up through the well is constant. This assumption requires that there are no heat losses from the well to the surroundings, which is a good approximation for a production well. Thus, if the enthalpy of the well has been found, the state of the fluid at top of the well can be calculated as a function of wellhead pressure, p_w, by following constant enthalpy lines. This is shown in Figure 3 (Pálsson, 2007).

3.2.2 Steam separator

A steam separator is a device for separating water from steam in a two-phase flow. The device is rather simple, and is based on creating a vortex which drives the heavy particles of the flow (water droplets) to one side, due to centrifugal force. This results in almost dry steam flowing from outlet of a separator, and pure water flowing from another outlet. Figure 7 shows a general layout of a separator.

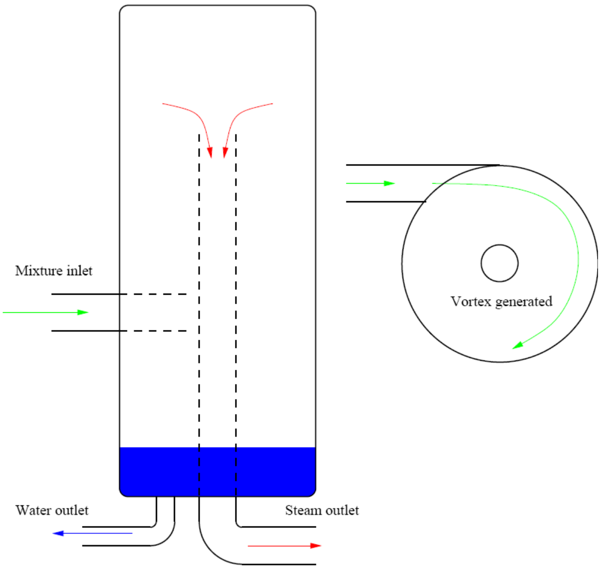

Figure 7: Schematic figure of a steam separator (Pálsson, 2007).

The process of an ideal separator is relatively simple since the state of the outlets is saturated water and saturated steam. Figure 8 shows the process on a T-s diagram (Pálsson, 2007).

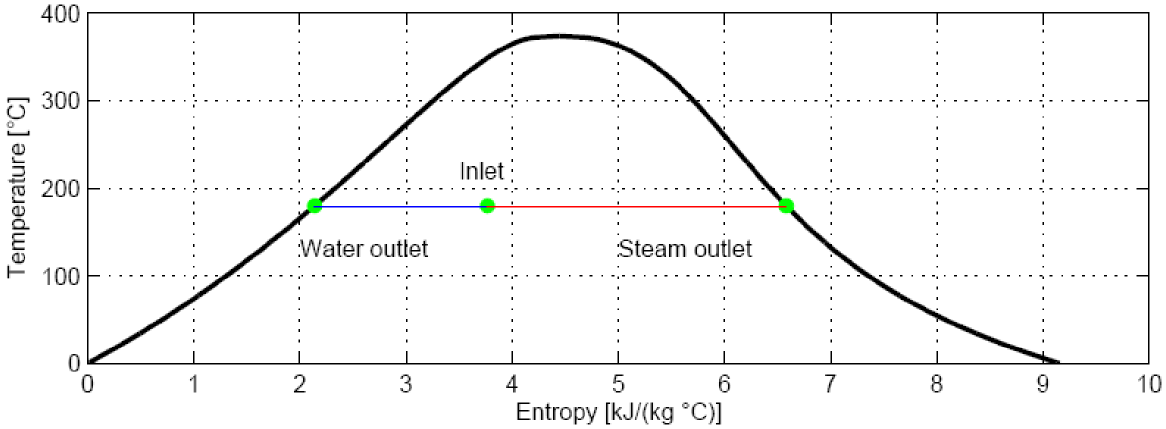

Figure 8: Separator process on a $T-s$ diagram (Pálsson, 2007).

3.3 Turbine - Generator

The turbine - Generator is the core unit of a geothermal power plant and is an expensive part which is very sensitive with regards to operating conditions.

In an ideal turbine, we consider the process to be isenthalpic where s is constant. This is generally not the case and turbines are classified with an efficiency parameter η_t. The efficiency is defined as

$$\eta_t = \frac{W_t}{W_s} \tag{4}$$

Where W_t and W_s are the real power output of turbine and the power output of an ideal turbine, respectively.

Figure 9 shows the process, the blue line denotes an ideal turbine and the red line a turbine with 85% efficiency.

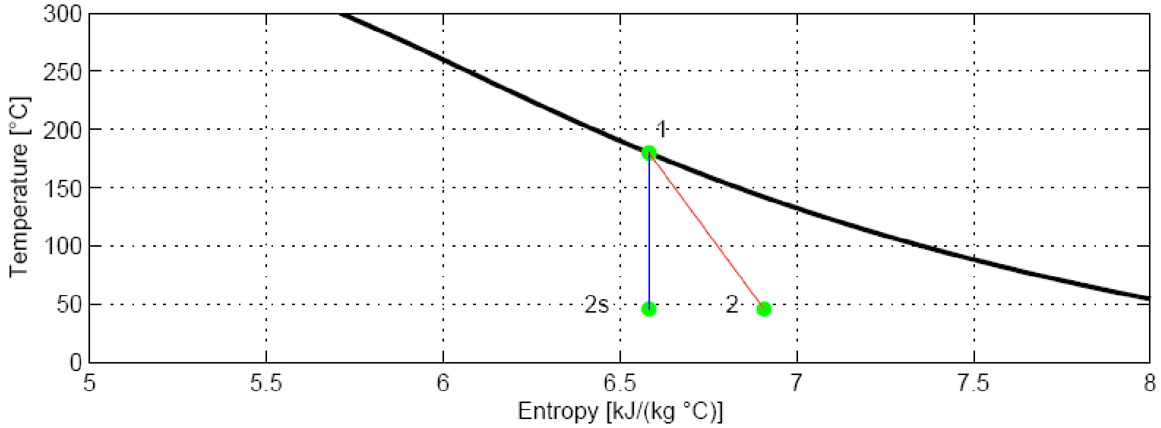

Figure 9: Steam turbine process on a $T-s$ diagram (Pálsson, 2007).

Also generators are classified with an efficiency parameter η_g. The efficiency is defined as:

$$\eta_g = \frac{W_g}{W_t} \tag{5}$$

Where W_g and W_t are the real power output of generator and the real power output of turbine or the power output of an ideal generator, respectively.

In this paper we assume $\eta_t = 0.85$ and $\eta_g = 0.90$.

It is obvious that there is an increase in entropy during the real process, if we assume the case is ideal, the entropy of fluid from turbine exit is the same entropy of input steam so:

$$s_{2s} = s_g \tag{6}$$

Based on the entropy of fluid from turbine exit and the pressure of condenser we could get enthalpy of fluid h_2, and the power out of turbine – generator could calculate from equations (7) to (9).

$$W_s = \dot{m}(h_2 - h_0) \tag{7}$$

$$W_t = \eta_t W \tag{8}$$

$$W_g = \eta_g W \tag{9}$$

Geothermal power cycle has some equipment such as condenser, cooling tower and gas compressor which we do not explain them in this paper.

4. CALCULATIONS

Based on the curves shown in Figure 5, we assumed five points with well head pressure (WHP) 9.5, 9.8, 10.0, 11.5 and 12.5 bar and find the total mass flow (kg/s), enthalpy (kj/kg) and steam flow (kg/s) from the curves shown in Figure 5. These parameters are listed in Table 3.

Table 3: Parameters of two-phase flow of NWS wells

WHP (Bar)	Total Mass Flow (kg/s)	Enthalpy (kj/kg)	Steam Flow (kg/s)
9.5	55	1183	13.7
9.8	53	1186	13.3
10.0	52	1188	12.8
11.5	40	1206	10.3
12.5	34	1215	8.8

A single flash power cycle is assumed with barometric pressure 0.72 bar and condenser pressure 0.13 bar, as shown in Figure 10.

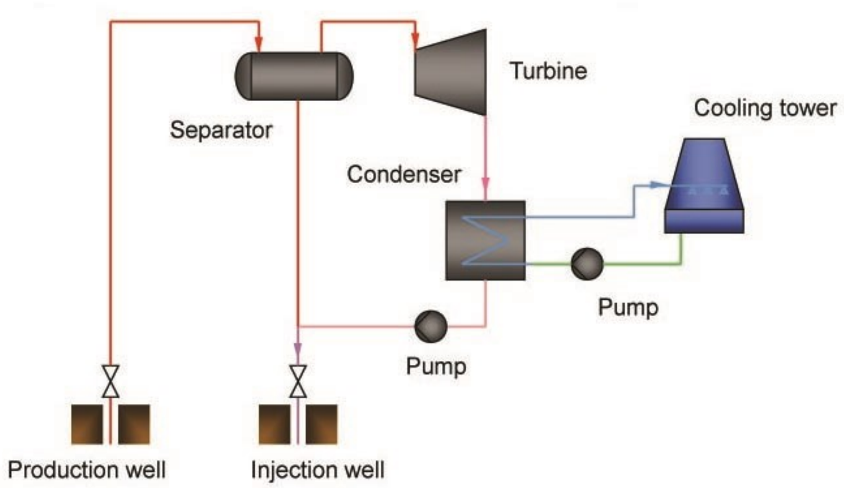

Figure 10: Single flash – Condensing power cycle (Valdimarsson, 2007)

For each of WHP that shown in Table 3 we assume various pressures for separator (these pressures could be obtained by throttle valve), then calculate the output steam flow from separator, which it will go to turbine. Now based on the Equations (7) to (9) the output power of turbine – generator could be calculated. For each of WHP we had some graphs that shown in Figure 11 to Figure 15 and also the results are shown in Table 5 to Table 9 at APPENDIX I.

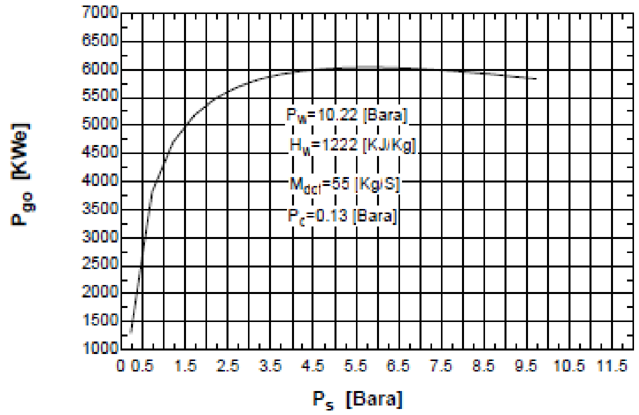

Diagram 11- Trend output power versus separator pressure (WHP=9.5 Barg)

Figure 11: Diagram of output power versus separator pressure (WHP= 9.5 Bar)

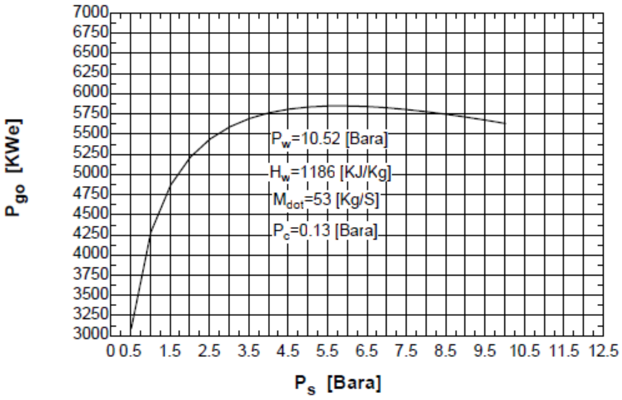

Figure 12: Diagram of output power versus separator pressure (WHP= 9.8 Bar)

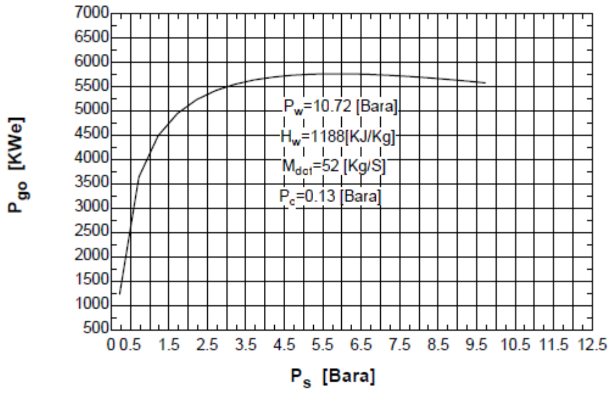

Figure 13: Diagram of output power versus separator pressure (WHP= 10.0 Bar)

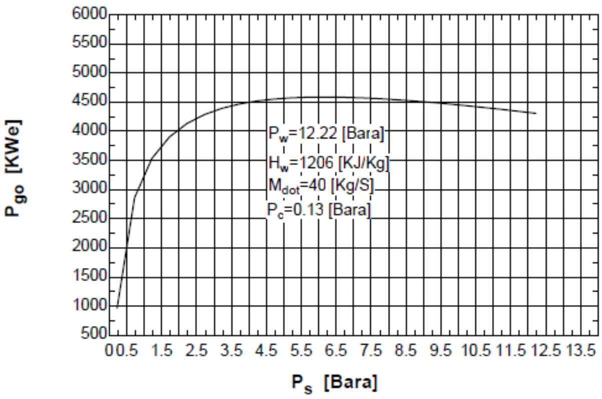

Figure 14: Diagram of output power versus separator pressure (WHP= 11.5 Bar)

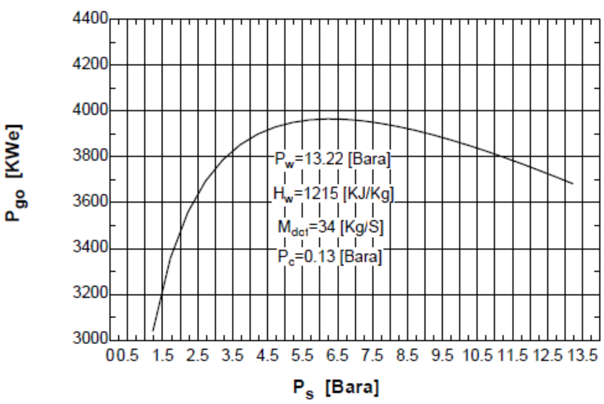

Figure 15: Diagram of output power versus separator pressure (WHP= 12.5 Bar)

5. CONCLUSIONS

In this paper a single flash power plant as shown in Figure 10 was assumed. The steam flow from NWS6-D and the well head pressure (WHP) 9.5, 9.8, 10.0, 11.5 and 12.5 bar was used to find the optimum separator pressure that had the maximum output power. The results are listed in Table 4.

Table 4: Optimum separator pressure and the maximum output power

WHP (Bar)	Total Mass Flow (kg/s)	Enthalpy (kj/kg)	Steam Flow (kg/s)	Optimum Separator Pressure (Bar)	Maximum Output Power (KWe)
9.5	55	1183	13.7	5.0	6036
9.8	53	1186	13.3	5.3	5850
10.0	52	1188	12.8	5.0	5762
11.5	40	1206	10.3	5.5	4587
12.5	34	1215	8.8	5.5	3695

These results demonstrate that for the WHP=9.5 bar with a separator pressure of 5.0 bar we had 6036 KWe power. As shown in Table 4, when the WHP goes high the power comes down.

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APPENDIX I: Tables of results

Table 5: Results for WHP=9.5 Bar

	P_w [Bara]	H_w [KJ/Kg]	$\dot{M}$ [Kg/S]	P_o [Bara]	T_w [C]	P_M [Bar]	X_w	P_c [Bara]	T_c [C]	X_c	$\dot{M}_{ss}$ [Kg/S]	T_o [C]	X_o	P_{go} [KWe]	Ef_{to} [%]
Run 1	10.22	1183	55	0.13	180.8	0.5	0.2068	9.72	178.7	0.2108	11.59	51.02	0.8424	5829	18.11
Run 2	10.22	1183	55	0.13	180.8	1	0.2068	9.22	176.4	0.2149	11.82	51.02	0.8444	5871	17.9
Run 3	10.22	1183	55	0.13	180.8	1.5	0.2068	8.72	174	0.2191	12.05	51.02	0.8464	5909	17.68
Run 4	10.22	1183	55	0.13	180.8	2	0.2068	8.22	171.6	0.2236	12.3	51.02	0.8486	5944	17.45
Run 5	10.22	1183	55	0.13	180.8	2.5	0.2068	7.72	169	0.2281	12.55	51.02	0.8509	5975	17.21
Run 6	10.22	1183	55	0.13	180.8	3	0.2068	7.22	166.2	0.2329	12.81	51.02	0.8534	6000	16.94
Run 7	10.22	1183	55	0.13	180.8	3.5	0.2068	6.72	163.3	0.2379	13.09	51.02	0.856	6020	16.66
Run 8	10.22	1183	55	0.13	180.8	4	0.2068	6.22	160.3	0.2432	13.38	51.02	0.8588	6033	16.35
Run 9	10.22	1183	55	0.13	180.8	4.5	0.2068	5.72	157	0.2488	13.68	51.02	0.8619	6036	16.02
Run 10	10.22	1183	55	0.13	180.8	5	0.2068	5.22	153.5	0.2547	14.01	51.02	0.8652	6030	15.65
Run 11	10.22	1183	55	0.13	180.8	5.5	0.2068	4.72	149.7	0.261	14.36	51.02	0.8688	6009	15.24
Run 12	10.22	1183	55	0.13	180.8	6	0.2068	4.22	145.6	0.2678	14.73	51.02	0.8729	5972	14.79
Run 13	10.22	1183	55	0.13	180.8	6.5	0.2068	3.72	141	0.2752	15.14	51.02	0.8774	5912	14.28
Run 14	10.22	1183	55	0.13	180.8	7	0.2068	3.22	136	0.2834	15.58	51.02	0.8825	5821	13.69
Run 15	10.22	1183	55	0.13	180.8	7.5	0.2068	2.72	130.2	0.2925	16.09	51.02	0.8886	5688	13
Run 16	10.22	1183	55	0.13	180.8	8	0.2068	2.22	123.5	0.3029	16.66	51.02	0.8958	5492	12.16
Run 17	10.22	1183	55	0.13	180.8	8.5	0.2068	1.72	115.5	0.3153	17.34	51.02	0.9049	5194	11.1
Run 18	10.22	1183	55	0.13	180.8	9	0.2068	1.22	105.3	0.3307	18.19	51.02	0.9172	4714	9.656
Run 19	10.22	1183	55	0.13	180.8	9.5	0.2068	0.72	90.67	0.3521	19.37	51.02	0.9363	3824	7.42
Run 20	10.22	1183	55	0.13	180.8	10	0.2068	0.22	62.12	0.3923	21.58	51.02	0.9801	1299	2.304

Table 6: Results for WHP=9.8 Bar

	P_w [Bara]	H_w [KJ/Kg]	$\dot{M}$ [Kg/S]	P_o [Bara]	T_w [C]	P_M [Bar]	X_w	P_c [Bara]	T_c [C]	X_c	$\dot{M}_{cc}$ [Kg/S]	T_o [C]	X_o	P_{go} [KWe]	Ef_{to} [%]
Run 1	10.52	1186	53	0.13	182.1	0.5	0.206	10.02	180	0.2099	11.12	51.02	0.8412	5632	18.23
Run 2	10.52	1186	53	0.13	182.1	1	0.206	9.52	177.8	0.2139	11.34	51.02	0.8432	5673	18.03
Run 3	10.52	1186	53	0.13	182.1	1.5	0.206	9.02	175.5	0.2181	11.56	51.02	0.8452	5711	17.82
Run 4	10.52	1186	53	0.13	182.1	2	0.206	8.52	173.1	0.2224	11.78	51.02	0.8473	5746	17.59
Run 5	10.52	1186	53	0.13	182.1	2.5	0.206	8.02	170.5	0.2268	12.02	51.02	0.8495	5778	17.36
Run 6	10.52	1186	53	0.13	182.1	3	0.206	7.52	167.9	0.2315	12.27	51.02	0.8519	5805	17.1
Run 7	10.52	1186	53	0.13	182.1	3.5	0.206	7.02	165.1	0.2364	12.53	51.02	0.8544	5826	16.83
Run 8	10.52	1186	53	0.13	182.1	4	0.206	6.52	162.1	0.2415	12.8	51.02	0.8571	5842	16.54
Run 9	10.52	1186	53	0.13	182.1	4.5	0.206	6.02	159	0.2468	13.08	51.02	0.86	5850	16.22
Run 10	10.52	1186	53	0.13	182.1	5	0.206	5.52	155.6	0.2525	13.38	51.02	0.8632	5849	15.87
Run 11	10.52	1186	53	0.13	182.1	5.5	0.206	5.02	152	0.2586	13.71	51.02	0.8666	5836	15.49
Run 12	10.52	1186	53	0.13	182.1	6	0.206	4.52	148.1	0.2651	14.05	51.02	0.8704	5809	15.07
Run 13	10.52	1186	53	0.13	182.1	6.5	0.206	4.02	143.8	0.2721	14.42	51.02	0.8746	5764	14.59
Run 14	10.52	1186	53	0.13	182.1	7	0.206	3.52	139.1	0.2798	14.83	51.02	0.8793	5694	14.05
Run 15	10.52	1186	53	0.13	182.1	7.5	0.206	3.02	133.8	0.2883	15.28	51.02	0.8848	5591	13.43
Run 16	10.52	1186	53	0.13	182.1	8	0.206	2.52	127.7	0.2978	15.79	51.02	0.8913	5440	12.68
Run 17	10.52	1186	53	0.13	182.1	8.5	0.206	2.02	120.5	0.3089	16.37	51.02	0.8992	5215	11.77
Run 18	10.52	1186	53	0.13	182.1	9	0.206	1.52	111.8	0.3223	17.08	51.02	0.9093	4869	10.58
Run 19	10.52	1186	53	0.13	182.1	9.5	0.206	1.02	100.2	0.3396	18	51.02	0.9237	4287	8.9
Run 20	10.52	1186	53	0.13	182.1	10	0.206	0.52	82.29	0.3655	19.37	51.02	0.9482	3090	6.027

Table 7: Results for WHP=10.0 Bar

	P_w [Bara]	H_w [KJ/Kg]	$\dot{M}$ [Kg/S]	P_o [Bara]	T_w [C]	P_M [Bar]	X_w	P_c [Bara]	T_c [C]	X_c	$\dot{M}_{cc}$ [Kg/S]	T_o [C]	X_o	P_{go} [KWe]	Ef_{to} [%]
Run 1	10.72	1188	52	0.13	182.9	1	0.2055	9.72	178.7	0.2133	11.09	51.02	0.8424	5576	18.11
Run 2	10.72	1188	52	0.13	182.9	1.5	0.2055	9.22	176.4	0.2174	11.3	51.02	0.8444	5614	17.9
Run 3	10.72	1188	52	0.13	182.9	2	0.2055	8.72	174	0.2216	11.52	51.02	0.8464	5650	17.68
Run 4	10.72	1188	52	0.13	182.9	2.5	0.2055	8.22	171.6	0.226	11.75	51.02	0.8486	5681	17.45
Run 5	10.72	1188	52	0.13	182.9	3	0.2055	7.72	169	0.2306	11.99	51.02	0.8509	5709	17.21
Run 6	10.72	1188	52	0.13	182.9	3.5	0.2055	7.22	166.2	0.2354	12.24	51.02	0.8534	5732	16.94
Run 7	10.72	1188	52	0.13	182.9	4	0.2055	6.72	163.3	0.2404	12.5	51.02	0.856	5750	16.66
Run 8	10.72	1188	52	0.13	182.9	4.5	0.2055	6.22	160.3	0.2456	12.77	51.02	0.8588	5760	16.35
Run 9	10.72	1188	52	0.13	182.9	5	0.2055	5.72	157	0.2512	13.06	51.02	0.8619	5762	16.02
Run 10	10.72	1188	52	0.13	182.9	5.5	0.2055	5.22	153.5	0.2571	13.37	51.02	0.8652	5754	15.65
Run 11	10.72	1188	52	0.13	182.9	6	0.2055	4.72	149.7	0.2634	13.7	51.02	0.8688	5733	15.24
Run 12	10.72	1188	52	0.13	182.9	6.5	0.2055	4.22	145.6	0.2702	14.05	51.02	0.8729	5696	14.79
Run 13	10.72	1188	52	0.13	182.9	7	0.2055	3.72	141	0.2775	14.43	51.02	0.8774	5637	14.28
Run 14	10.72	1188	52	0.13	182.9	7.5	0.2055	3.22	136	0.2857	14.85	51.02	0.8825	5549	13.69
Run 15	10.72	1188	52	0.13	182.9	8	0.2055	2.72	130.2	0.2948	15.33	51.02	0.8886	5420	13
Run 16	10.72	1188	52	0.13	182.9	8.5	0.2055	2.22	123.5	0.3052	15.87	51.02	0.8958	5231	12.16
Run 17	10.72	1188	52	0.13	182.9	9	0.2055	1.72	115.5	0.3175	16.51	51.02	0.9049	4946	11.1
Run 18	10.72	1188	52	0.13	182.9	9.5	0.2055	1.22	105.3	0.333	17.31	51.02	0.9172	4487	9.656
Run 19	10.72	1188	52	0.13	182.9	10	0.2055	0.72	90.67	0.3543	18.43	51.02	0.9363	3638	7.42
Run 20	10.72	1188	52	0.13	182.9	10.5	0.2055	0.22	62.12	0.3945	20.51	51.02	0.9801	1235	2.304

Table 8: Results for WHP=11.5 Bar

	P_w [Bara]	H_w [KJ/Kg]	$\dot{M}$ [Kg/S]	P_o [Bara]	T_w [C]	P_M [Bar]	X_w	P_c [Bara]	T_c [C]	X_c	$\dot{M}_{cc}$ [Kg/S]	T_o [C]	X_o	P_{go} [KWe]	Ef_{to} [%]
Run 1	12.22	1206	40	0.13	188.8	0	0.2036	12.22	188.8	0.2036	8.145	51.02	0.8337	4308	18.99
Run 2	12.22	1206	40	0.13	188.8	0.5	0.2036	11.72	186.9	0.2071	8.286	51.02	0.8353	4343	18.83
Run 3	12.22	1206	40	0.13	188.8	1	0.2036	11.22	185	0.2107	8.43	51.02	0.837	4377	18.66
Run 4	12.22	1206	40	0.13	188.8	1.5	0.2036	10.72	182.9	0.2144	8.578	51.02	0.8387	4409	18.49
Run 5	12.22	1206	40	0.13	188.8	2	0.2036	10.22	180.8	0.2182	8.73	51.02	0.8405	4440	18.3
Run 6	12.22	1206	40	0.13	188.8	2.5	0.2036	9.72	178.7	0.2222	8.887	51.02	0.8424	4468	18.11
Run 7	12.22	1206	40	0.13	188.8	3	0.2036	9.22	176.4	0.2262	9.05	51.02	0.8444	4495	17.9
Run 8	12.22	1206	40	0.13	188.8	3.5	0.2036	8.72	174	0.2304	9.218	51.02	0.8464	4519	17.68
Run 9	12.22	1206	40	0.13	188.8	4	0.2036	8.22	171.6	0.2348	9.392	51.02	0.8486	4541	17.45
Run 10	12.22	1206	40	0.13	188.8	4.5	0.2036	7.72	169	0.2393	9.574	51.02	0.8509	4559	17.21
Run 11	12.22	1206	40	0.13	188.8	5	0.2036	7.22	166.2	0.2441	9.763	51.02	0.8534	4573	16.94
Run 12	12.22	1206	40	0.13	188.8	5.5	0.2036	6.72	163.3	0.249	9.962	51.02	0.856	4583	16.66
Run 13	12.22	1206	40	0.13	188.8	6	0.2036	6.22	160.3	0.2543	10.17	51.02	0.8588	4587	16.35
Run 14	12.22	1206	40	0.13	188.8	6.5	0.2036	5.72	157	0.2598	10.39	51.02	0.8619	4584	16.02
Run 15	12.22	1206	40	0.13	188.8	7	0.2036	5.22	153.5	0.2656	10.63	51.02	0.8652	4573	15.65
Run 16	12.22	1206	40	0.13	188.8	7.5	0.2036	4.72	149.7	0.2719	10.88	51.02	0.8688	4552	15.24
Run 17	12.22	1206	40	0.13	188.8	8	0.2036	4.22	145.6	0.2786	11.14	51.02	0.8729	4518	14.79
Run 18	12.22	1206	40	0.13	188.8	8.5	0.2036	3.72	141	0.2859	11.44	51.02	0.8774	4467	14.28
Run 19	12.22	1206	40	0.13	188.8	9	0.2036	3.22	136	0.294	11.76	51.02	0.8825	4393	13.69
Run 20	12.22	1206	40	0.13	188.8	9.5	0.2036	2.72	130.2	0.3031	12.12	51.02	0.8886	4287	13
Run 21	12.22	1206	40	0.13	188.8	10	0.2036	2.22	123.5	0.3134	12.54	51.02	0.8958	4132	12.16
Run 22	12.22	1206	40	0.13	188.8	10.5	0.2036	1.72	115.5	0.3257	13.03	51.02	0.9049	3902	11.1
Run 23	12.22	1206	40	0.13	188.8	11	0.2036	1.22	105.3	0.341	13.64	51.02	0.9172	3535	9.656
Run 24	12.22	1206	40	0.13	188.8	11.5	0.2036	0.72	90.67	0.3622	14.49	51.02	0.9363	2861	7.42
Run 25	12.22	1206	40	0.13	188.8	12	0.2036	0.22	62.12	0.4021	16.08	51.02	0.9801	968.2	2.304

Table 9: Results for WHP=12.5 Bar

	P_w [Bara]	H_w [KJ/Kg]	$\dot{M}$ [Kg/S]	P_o [Bara]	T_w [C]	P_M [Bar]	X_w	P_c [Bara]	T_c [C]	X_c	$\dot{M}_{ss}$ [Kg/S]	T_o [C]	X_o	P_{go} [KWe]	Ef_{to} [%]
Run 1	13.22	1215	34	0.13	192.4	0	0.2014	13.22	192.4	0.2014	6.849	51.02	0.8307	3683	19.29
Run 2	13.22	1215	34	0.13	192.4	0.5	0.2014	12.72	190.6	0.2048	6.962	51.02	0.8322	3714	19.14
Run 3	13.22	1215	34	0.13	192.4	1	0.2014	12.22	188.8	0.2082	7.078	51.02	0.8337	3743	18.99
Run 4	13.22	1215	34	0.13	192.4	1.5	0.2014	11.72	186.9	0.2117	7.197	51.02	0.8353	3772	18.83
Run 5	13.22	1215	34	0.13	192.4	2	0.2014	11.22	185	0.2152	7.318	51.02	0.837	3800	18.66
Run 6	13.22	1215	34	0.13	192.4	2.5	0.2014	10.72	182.9	0.2189	7.444	51.02	0.8387	3826	18.49
Run 7	13.22	1215	34	0.13	192.4	3	0.2014	10.22	180.8	0.2227	7.573	51.02	0.8405	3851	18.3
Run 8	13.22	1215	34	0.13	192.4	3.5	0.2014	9.72	178.7	0.2266	7.706	51.02	0.8424	3874	18.11
Run 9	13.22	1215	34	0.13	192.4	4	0.2014	9.22	176.4	0.2307	7.843	51.02	0.8444	3896	17.9
Run 10	13.22	1215	34	0.13	192.4	4.5	0.2014	8.72	174	0.2349	7.985	51.02	0.8464	3915	17.68
Run 11	13.22	1215	34	0.13	192.4	5	0.2014	8.22	171.6	0.2392	8.133	51.02	0.8486	3932	17.45
Run 12	13.22	1215	34	0.13	192.4	5.5	0.2014	7.72	169	0.2437	8.287	51.02	0.8509	3946	17.21
Run 13	13.22	1215	34	0.13	192.4	6	0.2014	7.22	166.2	0.2484	8.447	51.02	0.8534	3957	16.94
Run 14	13.22	1215	34	0.13	192.4	6.5	0.2014	6.72	163.3	0.2534	8.615	51.02	0.856	3963	16.66
Run 15	13.22	1215	34	0.13	192.4	7	0.2014	6.22	160.3	0.2586	8.792	51.02	0.8588	3965	16.35
Run 16	13.22	1215	34	0.13	192.4	7.5	0.2014	5.72	157	0.2641	8.979	51.02	0.8619	3961	16.02
Run 17	13.22	1215	34	0.13	192.4	8	0.2014	5.22	153.5	0.2699	9.177	51.02	0.8652	3950	15.65
Run 18	13.22	1215	34	0.13	192.4	8.5	0.2014	4.72	149.7	0.2761	9.389	51.02	0.8688	3930	15.24
Run 19	13.22	1215	34	0.13	192.4	9	0.2014	4.22	145.6	0.2828	9.617	51.02	0.8729	3899	14.79
Run 20	13.22	1215	34	0.13	192.4	9.5	0.2014	3.72	141	0.2902	9.865	51.02	0.8774	3853	14.28
Run 21	13.22	1215	34	0.13	192.4	10	0.2014	3.22	136	0.2982	10.14	51.02	0.8825	3787	13.69
Run 22	13.22	1215	34	0.13	192.4	10.5	0.2014	2.72	130.2	0.3072	10.44	51.02	0.8886	3693	13
Run 23	13.22	1215	34	0.13	192.4	11	0.2014	2.22	123.5	0.3175	10.8	51.02	0.8958	3559	12.16
Run 24	13.22	1215	34	0.13	192.4	11.5	0.2014	1.72	115.5	0.3297	11.21	51.02	0.9049	3358	11.1
Run 25	13.22	1215	34	0.13	192.4	12	0.2014	1.22	105.3	0.345	11.73	51.02	0.9172	3040	9.656

$$Ef_{to} = P_{go} / (\dot{m}_s . h_s) * 100 \qquad (10)$$

Where Ef_{to}, P_{go}, $\dot{m}_s$ and h_s are the Total efficiency, the real power output of generator, the mass flow of steam after separator and the enthalpy of steam after separator, respectively