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Heat Exchanger Design on the Geothermal Binary Cycles in Dieng Geothermal Area, Indonesia

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ABSTRACT

Binary Cycle of geothermal plant was developed to utilize energy of waste geothermal water (brine) from Dieng Geothermal Plant to heat working fluid for electrical power generation. This paper describes energy balance on binary cycle which uses n-pentene (nC_5H_{12}) as working fluid and waste geothermal water (brine) as energy sources. The temperature of brine which will used is 174^{o}C, pressure of 700 kPa and mass flow rate of 6.75 kg/s, and then heated further in the evaporator by brine of brine 174^{o}C, pressure of 700 kPa and mass flow rate of 7.65 kg/s. From analysis of heat exchanger perfomances, total energy can be generated from this cycles is about 51 kW.

1. INTRODUCTION

As archipelagos country which is passed by vulcanic arc, Indonesia has many geothermal energy resources either from low, intermediate or high temperature. Total geothermal energy potential is about 28.8 Gwe from 299 geothermal prospects area (status of November 2012, source Badan Geologi KESDM). From this potential, only 1,226 Mwe of electrical power is generated from high temperature geothermal resources, while low and intermediate temperature of geothermal energy have not yet utilized for electrical power generation.

The government programme of 10,000 MW stage-II electricity development focused on new and renewable energy development and 40% from 10,000 MW will be developed from geothermal energy. This programme also in line with National Energy Regulation in Presidential Degree No.5/2006 regarding Energy Mix. Target of this programme is 5% of national energy contribution from geothermal until 2025.

Until now, In Indonesia, there is no utilization and development of low-intermediate temperature geothermal energy for electrical power generation. It is only reinjected to the reservoir with many reasons or left discharged into the river. The binary cycles is one of energy conversion technology which uses low-intermediate temperature heat source (100 ^{o}C>T<200 ^{o}C) either from geothermal source, solar energy or heat waste for heating working fluids that has low boiling temperature such as n-pentene, R134, R141 or other.

This binary cycles research and development activities have goals to utilize brine or waste energy of geothermal fluid which have temperature of 174^{o}C, pressure of 700 kPa and mass rate of 13.53 kg/s to generate electrical power with n-pentene (C_5H_{12}) as working fluid.

2. METHODOLOGY

The heat balance analysis of binary cycle system (see figure-1). This system uses brine with temperature of 174^{o}C and pressure of 765 kPa to heat n-pentene in preheater and evaporator. Then, steam of N-pentene is used to drive turbine and generator.

After driving turbine, steam of n-pentene is cooled in condenser until return to liquid and then it is recirculated. While after heating n-pentene, brine is reinjected into reservoir.

In this study is used shell and tube heat exchanger type i.e, preheater, evaporator and condenser.

To analyze heat exchanger performance, we must calculate overall heat transfer coefficient (U) by using equations as follows;

$$U_o = \frac{1}{\frac{A_o}{A_i}\frac{1}{h_i} + \frac{A_o \ln(ro/ri)}{2\Pi kL} + \frac{1}{h_o}} \quad (1)$$

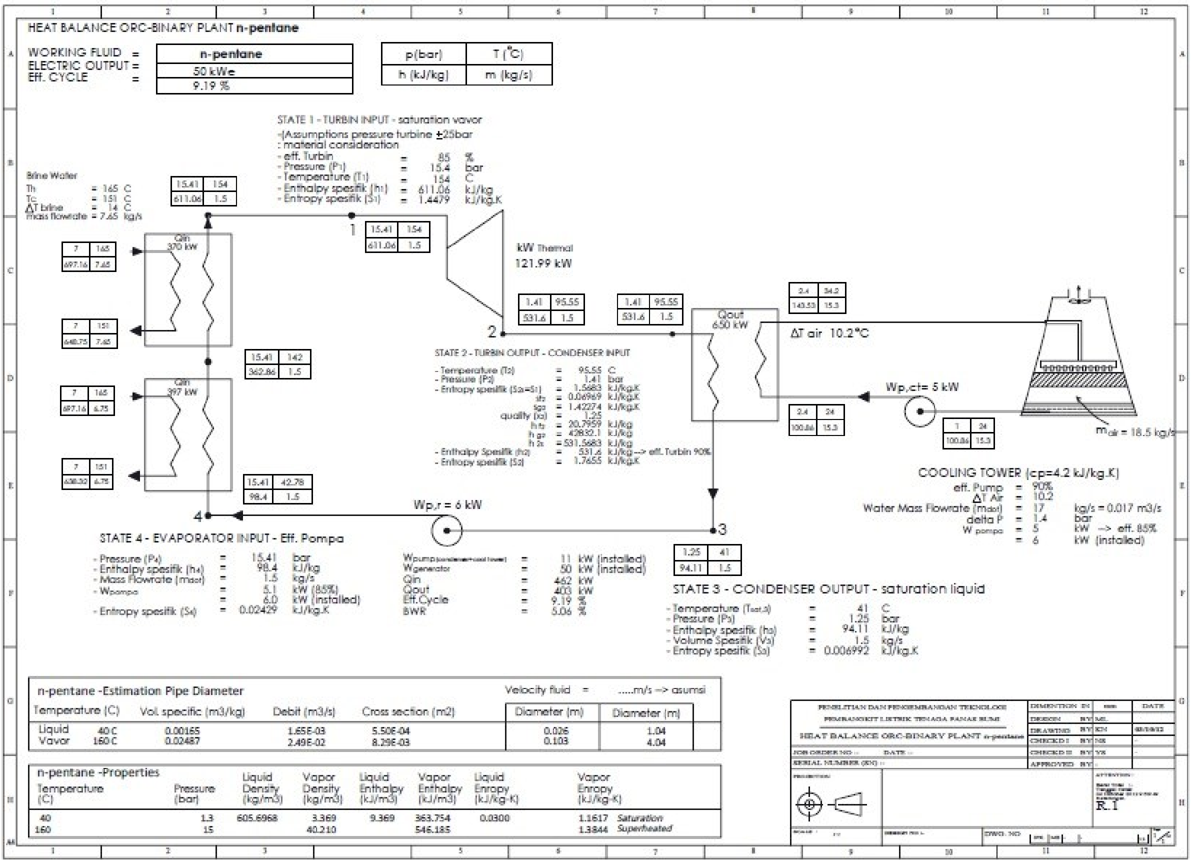

Figure 1: Heat Balance Analysis of Binary Cycles System

$$h_o = 0{,}725[\frac{\rho(\rho-\rho_v)gh_{fg}k_f^{\;3}}{\mu_f d(T_g - T_w)}]^{0,25} \tag{2}$$

$$h_i = \frac{N_u k_w}{D} \tag{3}$$

$$N_u = 0{,}023\ R_e^{0,8}\ P_r^{0,4} \tag{4}$$

$$R_e = \frac{Q.D.\rho}{\mu} \tag{5}$$

3. BINARY CYCLE COMPONENTS

3.1. Preheater

Preheater is a tool to preheat working fluid with hot fluid, here for heating n-pentene is used 6.75 kg/s brine with temperature of 174°C and pressure of 700 kPa or 7 bar. Figure-2 shows preheater component.

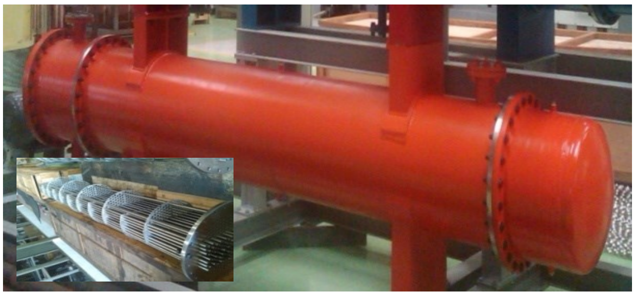

Figure 2: Preheater Component Shell and Tube Type

Preheater was designed with 212 tubes and tube specifications are ; outside diameter (OD) 15.87 mm, length 3 m and pitch 21.17 mm, and inside diameter (ID) shell is about 530 mm. Detailed technical data of the preheater can be seen in Appendix-1.

3.2. Evaporator

Evaporator is a tool which has function for heating working fluid after preheating in the Preheater. Brine with mass rate of 7.65 kg/s, temperature of 174°C and pressure of 700 kPa.

Evaporator was arranged by using 216 tubes of outside diameter (OD) 15.87 mm, length 3 m and pitch 23.81 mm. The inside diameter (ID) of Shell is about 430 mm. Detailed techincal data of the Evaporator are shown in Appendix-2. The evaporator is shown in Figure-3.

To prevent an explosion in the evaporator temperature working fluid coming out of the evaporator is controlled to not exceed the critical temperature of the working fluid. The n-pentene fluid cirtical condition is 193.85°C and a pressure of 3,250 kPa.

Figure 3: Shell and Tube Evaporator Type

3.3. Condenser

Condenser has the function to cool the working fluid that comes out of the turbine so that it returns to the liquid phase. Condenser was designed with a number of asa many as 444 pieces of tube with an outside diameter (OD) of 15.75 mm, 3 m long, 23.81 mm pitch with 6 number of pass and the Shell diameter of 530 mm. Detailed technical data of the cndenser can be seen in Appendix-3. Figure-4 shows the type of shell and tube condenser

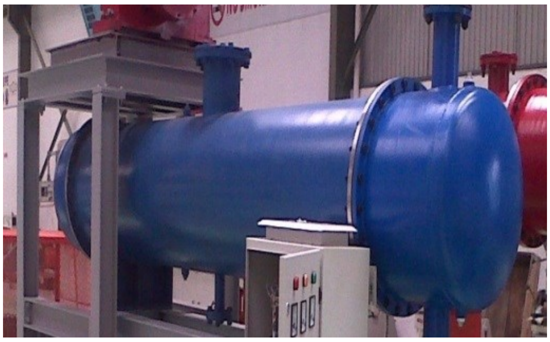

Figure 4: Shell and Tube Condenser type

3.4. Cooling Tower

Cooling tower serves to cool the cooling water after absorbing heat from the working fluida in the condenser. Figure-5 shows the type of mechanical draft cooling tower.

Figure 5: Mechanical Draft type of Cooling Tower

3.5. Turbine

Turbine used in this binary cycle system is radial inflow with a diameter of 448 mm of rotor, amount of rotor 110 pieces blades, nozzle length 35 mm, diameter 20 x 6 mm nozzle, nozzle material is AISI 304, the number of nozzle 6 pieces, with double mechanical seal of material stainless steel, tungsten and carbon with gear box ratio is 4 : 1.

Desaigned turbine working pressure of 1,500 kPa at 6,000 Rpm with a round that was later revealed to be 1,500 rpm in accordance with the rotation generator. Figure-6 shows the turbine of Binary Cycles.

Figure 6: Turbine of Binary cycles

The integration of all compponents of binary cycle can be seen in Figure-7 below;

Figure 7: Integration of All Components Binary Cycle

4. RESULT AND DISCUSSION

To determine the strength of the component preheater, evaporator and condenser has done pneumatic and hydrostatic test by pressing the 200 to 2,000 kPa pressure for 3 – 4 hours. The result of pneumatic and hydrostatic test is shown in Figure-8 below;

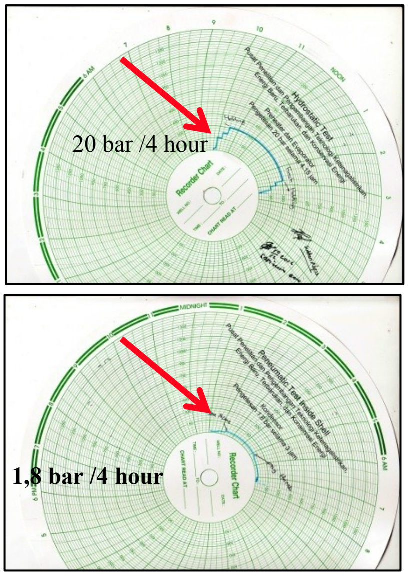

Figure 8: Hydrostatic and Pneumatic Test Result on Preheater, Evaporator and Condenser

From Figure-8 is known that preheater and evaporator components able to withstand a pressure of 2,000 kPa for 4 hours, and does not indicate a leak either in tubes and shell. In the real condition these components must withstand the pressure load of 1,000 to 1,500 kPa either from brine or working fluid. While condenser was designed to withstand pressure load of 120 kPa.

N-pentene with temperature 42^{o}C and flow rate of 1,5 kg/s and 6,7557 kg/detik brine with temperature of 174^{o}C is pumped to the preheater, here n-pentene absorbs heat from the brine about 422,3 kW thus raising the temperature of n-pentene from 42^{o}C to 142^{o}C, the pressure drop that occured in the preheater is equal to 0,676 kPa.

From preheater, n-pentene with temperature of 142^{o}C is heated further by 7.656 kg/s, 174^{o}C brine, here n-pentene absorb heat of 397.0 kW so that the temperature rose to 154^{o}C and turn into a vapor phase, this n-pentene vapor with pressure of 1519.07 kPa is then used to drive turbine.

Temperature and pressure of the superheated n-pentene vapor are lower than critical point of n-pentene, that is below temperature of 193.85^{o}C and maximum pressure of 3,250 kPa. The pressure drop that occured in the evaporator is about 1.91 kPa.

After driving turbine, n-pentene is chilled in the condenser by pumping 15.3 kg/s, 27^{o}C of water so that temperature of n-pentene decrease from 94,12 ^{o}C to 41^{o}C, here heat is released from n-pentene is about 687,3 kW.

Based on the analysis of the energy balance, the work produced by the vapor of n-pentene is about 121,99 kW thermal, if the total turbine and generator efficiency of 42%, the electrical power that can b generated by this binary cycle is about 51,23 kW.

5. CONCLUSIONS

1. Temperature of the superheated vapor of the n-pentene fluid that comes out from the evaporator is about 154^{o}C at pressure of 1519,07 kPa which is an inlet pressure of turbine.
2. To achieve this superheated conditions required by preheating the brine in the preheater. The temperature of brine is 174^{o}C, pressure of 700 kPa and mass flow rate of 6.75 kg/s, and then heated further in the evaporator by brine of brine 174^{o}C, pressure of 700 kPa and mass flow rate of 7.65 kg/s
3. To cool n-pentene from 94.12 ^{o}C to 41 ^{o}C is required water with temperature of 27 ^{o}C, pressure of 240 kPa and the mass flow rate of 15.3 kg/s
4. Turbine type is radial inflow with d*ouble m*echanical seal and 1:4 rasio of gear box. The electrical power output is about 51 kW.

SUBSCRIPTS

A_o = outer surface area of the tube

A_i = inner surface area of the tube

L = tube length

h_i = inside tube heat-transfer coefficient where cooling/heating fluid flows.

h_o = outside tube heat-transfer coefficient where working fluid flows.

k = pipe material heat conductiivity

ρ = density of liquid form of working fluid

ρ_v = density of vapor form of working fluid

h_{fg} = working fluid enthalpy

μ_f = dynamic viskosity of working fluid

k_f = heat conductivity of working fluid

d = inside diameter of tube

T_g = saturation temperature of condensate

T_w = wall temperature of tube

D = outside diameter of tube

Q = cooling water mass rate

k_w = heat conductivity of cooling water or brine

N_U = Nusselt number

P_r = Prantl number

R_e = Reynolds number

REFERENCES

Ayub Z.H., Plate Heat Hxchanger Literature Survey and New Heat Transfer and Pressure Drop Correlations for the Refigerant Evaporators, *Heat Transfer Engineering* 24 (5) (2003) 3-16.

Bell, K., J., 1988, Delaware *Method for Shell-Side Design, in Heat Transfer Equipment Design*, R.K. Shah, E.C, Subbarao, and R. A. Mashelkar, eds., Hemisphere Publishing, Washington, DC, pp. 145–166

Crane Co., 1976, *Flow of Fluids through Valves, Fittings, and Pipes*, Technical Paper 410, Crane Co., Chicago.

Cavallini, A., Zecchin, R. (1974). *A Dimensionless Correlation for Heat Transfer in Forced Convection Condensation*, 6th Interantional heat Transfer Conference, Vol.3, 309-313, Tokyo.

D.Chandrasekharam and Jochen Bundschuh, *Low-Enthalpy Geothermal Resources for Power Generation*, CRC ress/Balkema, Netherlands, 2008, hal 15.

Edwards, L.M., et al, *Handbook Of Geothermal Energy*, Gulf Publishing Company, USA. 1982, hal 58 -59 dan hal 431.

Stanley L. Milora and Jefferson W. Tester, *Geothermal Energy as a Source of Electric Power, Thermodynamic and Economic Design Criteria*, The MIT Press, Cambridge, Massachusetts, and London, England, Third printing, November 1977.

Ronald DiPippo, *Geothermal Power Plant, Principle, Application, Case Studies and Environmental Impact*, Dartmouth, Massachusetts, May 2007.

Grant, A. Malcolm, et al, "*Geothermal Reservoir Engineering*.", Academic Press. New York. 1982, hal 108 –146

Appendix-1

PREHEATER TECHNICAL DATA SPESIFICATIONS
BINARY CYCLE 50 kW

Process Conditions	Units	Cold Shell Side		Hot Tube Side	
		Inlet	Outlet	Inlet	Outlet
Fluid Name		N-pentene		Geothermal Fluid	
Flow rate	kg/s	1,500	1,500	6,756	6,756
Y (wt. Frac.vap.)	fraction	0,000	0,000	0,000	0,000
Temperature	^{o}C	42,000	142,000	174,000	159,650
Average Pressure	kPa	1529,020	1528,680	700,000	684,951
dPallow	kPa	0,676	0,000	15,049	0,000
Fouling	m^2K/W	0,000	0,000	0,000	0,000
Heat Exchanger Peformance					
Shell h	W/m^2K	626,62	Actual U	W/m^2K	555,04
Tube h	W/m^2K	8977,75	Required U	W/m^2K	231,84
Hot Regime	-	liquid	Duty	mW	0,4223
Cold Regime	-	liquid	Area	m^2	31,247
EMTD	^{o}C	58,3	Overdesign	%	139,4
Shell Geometry			**Baffle Geometry**		
TEMA Type	-	AEM	Baffle Type	-	Single
Shell ID	mm	430,00	Baffle Cut	Pct Dia.	30,00
Series	-	1,00	Baffle Orientation	-	Perpend.
Parallel	-	1,00	Central Spacing	mm	150,00
Orientation	-	0,00	Crosspasses	-	17,00
Tube Geometry			**Nozzles**		
Tube Type	-	Plain	Shell Inlet	mm	77,927
Tube OD	mm	15,875	Shell Outlet	mm	77,927
Length	m	3	Inlet Height	mm	9,815
Pitch Ratio	-	1,45	Outlet Height	mm	9,815
Layout	deg	60	Tube Inlet	mm	77,927
Tube Number	Pcs	212	Tube Outlet	mm	77,927
Tube Pass	-	4			
Thermal Resistance, %		**Velocities, m/s**		**Flow Fractions**	
Shell	88,58	Shell Side	0,10	A	0,141
Tube	7,28	Tube Side	0,99	B	0,705
Faouling	0,00	Crossflow	0,13	C	0,036
Metal	4,14	Windows	0,11	E	0,118

Appendix-2

EVAPORATOR TECHNICAL DATA SPESIFICATIONS BINARY CYCLE 50 kW

Process Conditions	Units	Cold Shell Side		Hot Tube Side	
		Inlet	*Outlet*	*Inlet*	*Outlet*
Fluid Name		N-pentene		Geothermal Fluid	
Flow rate	kg/s	1,500	1,500	7,656	7,656
Y (wt. Frac.vap.)	fraction	0,000	0,000	0,000	0,000
Temperature	°C	142,000	154,000	174,000	162,110
Average Pressure	kPa	1520,020	1519,070	700,000	681,483
dPallow	kPa	1,911	0,000	18,517	0,000
Fouling	m^2K/W	0,000	0,000	0,000	0,000
Heat Exchanger Peformance					
Shell h	W/m^2K	2632,89	Actual U	W/m^2K	1738,57
Tube h	W/m^2K	9754,91	Required U	W/m^2K	596,37
Hot Regime	-	liquid	Duty	mW	0,397
Cold Regime	-	Flow	Area	m^2	31,849
EMTD	°C	20,9	Overdesign	%	191,52
Shell Geometry			**Baffle Geometry**		
TEMA Type	-	AEM	Baffle Type	-	Single
Shell ID	mm	430,00	Baffle Cut	Pct Dia.	30,00
Series	-	1,00	Baffle Orientation	-	Parallel
Parallel	-	1,00	Central Spacing	mm	250,00
Orientation	-	0,00	Crosspasses	-	11,00
Tube Geometry			**Nozzles**		
Tube Type	-	Plain	Shell Inlet	mm	77,927
Tube OD	mm	15,875	Shell Outlet	mm	102,261
Length	m	3,000	Inlet Height	mm	26,210
Pitch Ratio	-	1,500	Outlet Height	mm	26,210
Layout	deg	60	Tube Inlet	mm	77,927
Tube Number	Pcs	216	Tube Outlet	mm	77,927
Tube Pass	-	4			
Thermal Resistance, %		**Velocities, m/s**		**Flow Fractions**	
Shell	66,03	Shell Side	0,62	A	0,107
Tube	21,00	Tube Side	1,10	B	0,835
Faouling	0,00	Crossflow	0,77	C	0,058
Metal	12,97	Windows	1,18	E	0,123

Appendix-3

CONDENSER TECHNICAL DATA SPESIFICATIONS
BINARY CYCLE 50 kW

Process Conditions	Units	Hot Shell Side		Cold Tube Side	
		Inlet	*Outlet*	*Inlet*	*Outlet*
Fluid Name		N-pentene		Water	
Flow rate	kg/s	1,500	1,500	15,300	15,300
Y (wt. Frac.vap.)	fraction	1,000	0,000	0,000	0,000
Temperature	^{o}C	94,120	41,000	27,000	37,750
Average Pressure	kPa	140,020	138,492	240,003	210,509
dPallow	kPa	3,020	0,000	58,990	0,000
Fouling	m^2K/W	0,000	0,000	0,000	0,000
Cooling Exchanger Peformance					
Shell h	W/m^2K	1194,30	Actual U	W/m^2K	918,61
Tube h	W/m^2K	7092,03	Required U	W/m^2K	754,93
Hot Regime	-	Shear	Duty	mW	0,6873
Cold Regime	-	Liquid	Area	m^2	65,362
EMTD	^{o}C	13,9	Overdesign	%	21,68
Shell Geometry			**Baffle Geometry**		
TEMA Type	-	AEM	Baffle Type	-	Single
Shell ID	mm	530,00	Baffle Cut	Pct Dia.	40,00
Series	-	1,00	Baffle Orientation	-	Parallel
Parallel	-	1,00	Central Spacing	mm	330,00
Orientation	-	0,00	Crosspasses	-	8,00
Tube Geometry			**Nozzles**		
Tube Type	-	Plain	Shell Inlet	mm	258,877
Tube OD	mm	15,875	Shell Outlet	mm	77,927
Length	m	3,000	Inlet Height	mm	7,803
Pitch Ratio	-	1,333	Outlet Height	mm	7,803
Layout	deg	60	Tube Inlet	mm	102,261
Tube Number	Pcs	444	Tube Outlet	mm	102,261
Tube Pass	-	6			
Thermal Resistance, %		**Velocities, m/s**		**Flow Fractions**	
Shell	76,92	Shell Side	4,48	A	0,105
Tube	15,36	Tube Side	1,48	B	0,666
Faouling	0,00	Crossflow	5,48	C	0,065
Metal	7,72	Windows	5,60	E	0,073