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COMPARATIVE STUDY OF PRIMARY FLUID FLOW (PFF) FREESTON METHOD AND NUMERICAL METHOD BY COMPUTATIONAL SIMULATION ON STEAM JET EJECTOR AT PLTP XXXX

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ABSTRACT

In producing better power plant efficiency, steam produced at geothermal wells undergoes reduction of NCG (Non Condensable Gas) percentage. This reduction is followed by steam consumption required by steam jet ejector to separate NCG. NCG percentage variation with PFF (Primary Fluid Flow) mass rate is display to tell the amount saving can be produced. As one of popular methods in predicting the amount NCG reduced in ejector, Freeston method gives suggestion to calculate PFF mass rate ATSR graphic (Air To Steam Ratio). To better produce better prediction, the result of the Freeston method (1) is compared to computational results in this study using PLTP (Geothermal Power Plant) XXXX data.

As the change of PFF mass rate required on first and second stage steam jet ejector, it is necessary to remodel GRS (Gas Removal System) at PLTP XXX such as intercondenser and aftercondenser. Simulation and remodeling is conducted for NCG percentage variation: 0.5-3.375% for first stage ejector and intercondenser and 0.5-1.5% for second stage ejector and aftercondenser. The current study found that the average of ATSR percentage difference between Freeston method and computation on first stage ejector is 16.31% while on second stage ejector is 17.60%. PFF mass rate required by first and second stage will increase with increase of NCG percentage. The requirement of mass rate of cooling water condensate on intercondenser and aftercondenser will decrease with increase of NCG percentage.

INTRODUCTION

There are so many discussions about efficiency of net delivery capacity or net power output produced by power plant (2,3,4,5) for example, LRVP (Liquid Ring Vacuum Pump) will be not reused again in order to decrease electric consumption of gas removal system and reduction of PFF for ejector performance. Normally, the amount of NCG produced by a steam well will decrease over the time, and this decrease should also decrease the usage of PFF to run the ejector performance. There is formula that suggests the magnitude of minimum PFF to run ejector the saving cost off PFF usage can be calculated. One popular method in determining the magnitude of minimum PFF was introduced by Freeston (6). The objective of current study is to compare Freeston method formula and numerical/ computational simulation results in calculating the amount PFF use.

FREESTON METHOD

ER (Entrainment Ratio) indicates the performance parameter to determine whether the ejector is on the optimum performance or not as described in Eq. [1] and Fig. 1.

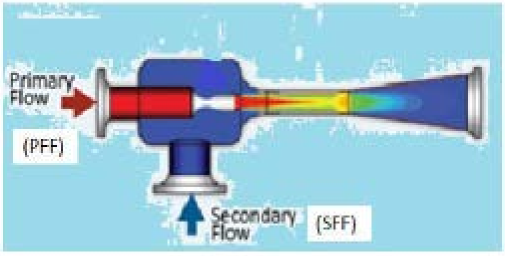

Figure 1. Flow Definition in Ejector

$$\text{Entrainment Ratio (ER)} = \frac{\text{Secondary Fluid Flow}\left(\frac{kg}{s}\right)}{\text{Primary Fluid Flow}\left(\frac{kg}{s}\right)} = \frac{SFF\left(\frac{kg}{s}\right)}{PFF\left(\frac{kg}{s}\right)} \quad [1]$$

The higher PFF from steam well, the lower the value of ER. It means that to increase ER, the amount of PFF or steam from well should be reduced and the SFF should be drawn as much as possible from condenser. Freeston method has another definition of performance described as ATSR (Air To Steam Ratio) as written in Eq. [2].SC (Steam Consumption) has same definition with PFF with DAE (Dry Air Equivalent) has different definition as described in Eq. [3]. $\dot{m}$ is the flow rate and DAE is SFF evaluated at standard temperature of 70^0F (21^0C) with all properties in fluid is evaluated at that temperature.

$$ATSR = \frac{DAE}{SC} \quad [2]$$

$$DAE = \frac{\dot{m}_{uap}}{Tcf_{uap} x Mer_{uap}} + \frac{\dot{m}_{NCG}}{Tcf_{NCG} x Mer_{NCG}} \quad [3]$$

To get T_{cf} (Temperature correction factor), Fig. 2 is used and to get M_{er} (Mass Molecular correction factor), Fig.3 is used.

MODELING GRS (GAS REMOVAL SYSTEM)

Modeling is conducted in PLTP XXXX ejector as shown in Fig. 4 (7). There are four components in this PLTP Gas Removal System: Two ejectors, one intercondenser, and one aftercondenser and the simulation were conducted at these four components.

Outputs of ejector modeling are: PFF mass rate (kg/s) on motive steam inlet and suction inlet pressure (barA). Output of intercondenser and aftercondenser modeling are the relation between NCG percentage variation and cooling water mass rate from cooling tower with condensate mass rate entering main condenser.

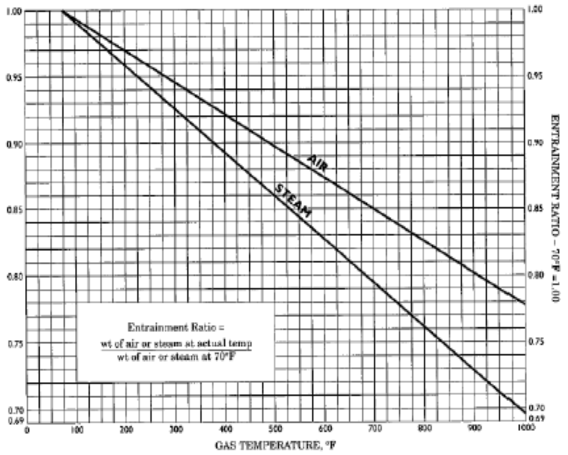

Figure 2. Temperature correction factor[3]

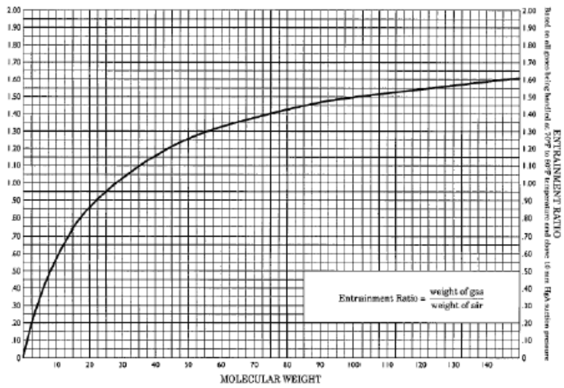

Figure 3. Mass molecular correction factor[3]

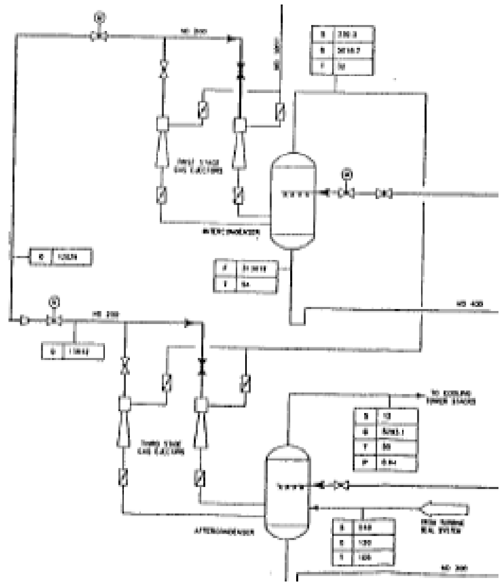

Figure 4. Gas Removal System in PLTP XXXX

MODELING ON FIRST AND SECOND EJECTOR

First ejector used NCG percentage variation range of 0.5-3.375% with increment of 0.25%. The selection of that lower range number is due to the trend of NCG percentage that is never below 0.5% and the selection of that upper range number is due to the fact that at the further calculation in ATSR (Air To Steam Ratio) formula that would show that DAE value must be higher than PFF.

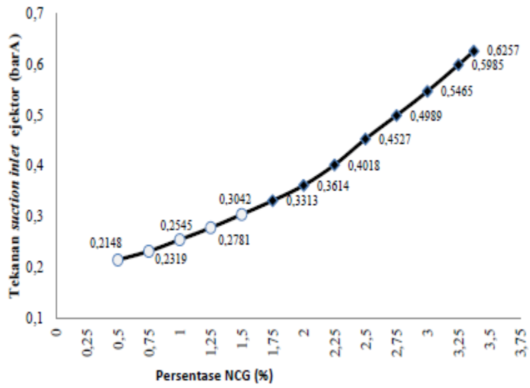

Figure 5. Relation of suction inlet pressure on 2nd ejector with NCG percentage variation

At the second ejector, simulation is made for NCG percentage varies 0.5% - 1.5%. This range is picked due to the fact that at 1.75% until 3.375%, the suction inlet pressure obtained from computational simulation is higher than intercondenser pressure as shown in Fig. 5. If it happens, fluid flow will occur from second ejector to intercondenser. Figure 4shows the magnitude of suction inlet pressure toward NCG percentage variation.

BOUNDARY CONDITION OF FIRST AND SECOND EJECTOR

1. Suction Inlet

Table 1 shows input parameter on first ejector suction inlet.

Table 1. Input parameter simulation for first ejector

Persentase NCG (%)	*Secondary Fluid Flow* (SFF)						Total SFF (kg/s)
	NCG (kg/s)	NCG (%)	Udara (kg/s)	Udara (%)	Uap (kg/s)	Uap (%)	
0,500	0,550	0,499	0,067	0,061	0,486	0,441	1,103
0,750	0,825	0,599		0,049		0,353	1,378
1,000	1,100	0,665		0,041		0,294	1,653
1,250	1,375	0,713		0,035		0,252	1,928
1,500	1,650	0,749		0,030		0,221	2,203
1,750	1,925	0,777		0,027		0,196	2,478
2,000	2,200	0,799		0,024		0,177	2,753
2,250	2,475	0,817		0,022		0,161	3,028
2,500	2,750	0,833		0,020		0,147	3,303
2,750	3,025	0,845		0,019		0,136	3,578
3,000	3,300	0,856		0,017		0,126	3,853
3,250	3,575	0,866		0,016		0,118	4,128
3,375	3,712	0,870		0,016		0,114	4,265

Based on Table 1, steam mass rate entering the main condenser is 109.99 kg/s. On the first ejector, steam and air mass rate entering suction inlet are assumed to be unchanged at each NCG percentage variation. The magnitude of Steam mass rate is 0.486 kg/s and air mass rate is 0.067 kg/s. With these mass rates, the percentage of each fluid in total mixture entering first ejector suction inlet can be known.

On the second ejector, it is assumed that steam mass rate has same number on each NCG percentage variation: 0.109 kg/s. Other assumptions are: NCG and air mass rate from intercondenser to the second ejector has the same mass rate for both fluids from the first ejector to intercondenser. On these boundary conditions, the pressure will be obtained using numerical simulations. In this calculation, the magnitude of temperature is maintained at 28^{0}C. Complete parameters are presented in Table 2.

Table 2. Input parameter simulation for second ejector

Persentase NCG (%)	Secondary Fluid Flow (SFF)						Total SFF (kg/s)
	NCG (kg/s)	NCG (%)	Udara (kg/s)	Udara (%)	Uap (kg/s)	Uap (%)	
0,50	0,569	0,764	0,067	0,090	0,109	0,146	0,744
0,75	0,853	0,829		0,065		0,106	1,028
1,00	1,137	0,866		0,051		0,083	1,313
1,25	1,421	0,890		0,042		0,068	1,597
1,50	1,706	0,907		0,036		0,058	1,881

2. Motive Steam Inlet

Based on P&ID description of the PLTP, NCG percentage either in first ejector or in second ejector is assume to have same number with NCG percentage in the steam well. The magnitude of pressure at this boundary conditions is 6,3 barA and has temperature at 161^{0}C.

3. Outlet Ejector

Percentage of each species on outlet first ejector is H_2O 70.4%, NCG 28.5%, and air 1.1 %. Percentage of each species on outlet second ejector is H_2O 68.93%, NCG 29.95%, and air 1.14 %[4]. These data is used in numerical simulation as initial value due to implicit condition. The NCG is assumed to have same characteristic as CO_2 on numerical simulation because the largest species of NCG is CO_2(almost 90%). This assumption is necessary to simplify the problem.

The pressure on outlet first ejector of 0.31 barAhas same number with operating pressure of intercondenser. The temperature of the first ejector changes proportionally with the change of NCG percentage variation, but as the initial value in numerical simulations, temperature of outlet of first ejector is 108^{0}C[4]. The pressure of outlet of the second ejector is set to 0,94 barA[4]. The numerical simulation yields the higher pressure of suction inlet than intercondenser operating pressure (0,31 barA). It would create backflow from the second ejector to intercondenser. To avoid this, the pressure on outlet ejector must be adjusted so that the pressure on suction inlet second ejector is lower than intercondenser operating pressure with pressure on that ejector must be higher than atmospheric pressure. The total atmospheric pressure on certain altitude can be calculated using Eq. [4] (8).

$$P = P_o[1 - \left(\frac{L_s Z}{T_0}\right)]^{\frac{gM_{ud}}{RL}} \quad [4]$$

The altitude of the power plant is 1350 m above the sea[11], so the total atmospheric pressure on the plant that obtained from Eq. [4] is 0,861 barA. For numerical simulation with the operating pressure of aftercondenser or pressure of the outlet second ejector is 0,87 barA (still higher than atmospheric pressure), the suction inlet pressure is 0,3 barA which is still lower than intercondensor operating pressure. It means that at 0,87 barA of aftercondenser, the fluid will flow from intercondenser to the second ejector. Table 3 shows input parameter for each boundary condition for numerical simulation.

Table 3. Input parameter for each boundary conditions. Asterisk (*) indicates the magnitude are unknown and would be calculated using

Ejektor Tingkat Satu			
	Motive steam inlet	*Suction*	Outlet
Tekanan (barA)	6,3	(*)	0,31
Temperatur Total (K)	434	301	(*)
Ejektor Tingkat Dua			
Tekanan (barA)	6,3	(*)	0,87
Temperatur Total (K)	434	301	(*)

MODELING ON INTERCONDENSER AND AFTERCONDENSER AFTER MODIFICATION OF PFF MASS RATE ON FIRST AND SECOND EJECTOR

After numerical simulations on first ejector and second ejector, there are some changes on intercondenser and aftercondenser and intercondenser and aftercondenser parameter conditions like pressure, temperature, and mass flow rate must adjusted.

1. Intercondenser

There are two inlets and two outlets on intercondenser as shown in Fig. 6. Two inlets come from first outlet ejector and cooling tower and two outlets go into second ejector and main condenser.

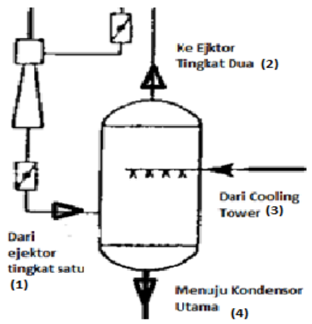

Figure 6. Mass balance in Intercondenser

For input parameter new intercondenser model, data of Tables 4 and 5 are used. To calculate cooling tower mass rate to intercondenser and main condenser mass rate from intercondenser, Eq. 5 and 6 are used respectively. The first outlet temperature is shown in Fig. 7.

Table 4. Input parameter for intercondenser pressure and temperature

	Parameter		Pressure (barA)	Temperature (K)
INLET	1st outlet ejector (1)	H_2O (kg/s)	0,31	From figure 4
		CO_2(kg/s)		
		Udara (kg/s)		
	Cooling Tower (3)	H_2O (kg/s)		299
OUTLET	2nd suction inlet ejector (2)	H_2O (kg/s)		301
		CO_2(kg/s)		301
		Udara (kg/s)		301
	Main Condenser (4)	H_2O (kg/s)		329

Table 5. Input parameter for intercondenser mass rate

	Parameter		Mass rate (kg/s)
INLET	1st Outlet Ejector (1)	H_2O (kg/s)	[Summation of PFF and SFF]
		CO_2(kg/s)	
		Air (kg/s)	
	Cooling Tower (3)	H_2O (kg/s)	[From Equation 3]
OUTLET	2nd Suction inlet ejector (2)	H_2O (kg/s)	0,109
		CO_2(kg/s)	Same as 1st outlet ejector mass rate
		Air (kg/s)	
	Main Condenser (4)	H_2O (kg/s)	[From Equation 4]

$$\dot{m}_{h2o(3)} = \frac{1}{h_{h2o(4)} - h_{h2o(3)}} \left(\dot{m}_{h2o(1)} \Delta h_{h20\,(1-4)} + \dot{m}_{co2(1)} \Delta h_{co2(1-2)} + \dot{m}_{udara(1)} \Delta h_{udara(1-2)} - \dot{m}_{h2o(2)} \Delta h_{h20\,(2-4)}\right) \quad [5]$$

$$\dot{m}_{h2o(4)} = \dot{m}_{h2o(1)} + \dot{m}_{h2o(3)} - \dot{m}_{h2o(2)} \quad [6]$$

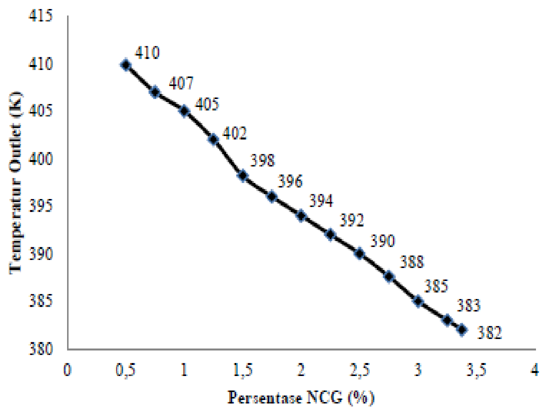

Figure 7. First outlet ejector temperature

2. Aftercondenser

There are three inlets and two outlets on aftercondenser as shown in Fig. 8. Three inlets come from the second outlet ejector, cooling tower, and turbine seal system. Mass flow from turbine seal system is 0.15 kg/s[4]. Two outlets go into Cooling Tower Stack and main condenser. For input parameter new intercondenser model, Tables 6 and 7 are used. To calculate cooling tower mass rate to aftercondenser and main condenser mass rate from aftercondenser, Eqs. 7 and 8 are used respectively

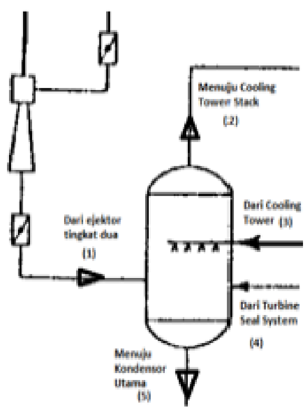

Figure 8. Fluid flow in Aftercondenser

Table 6. Input parameter for aftercondenser mass rate

	Parameter		Pressure (barA)	Temperature (K)
INLET	2nd outlet ejector (1)	H_2O (kg/s)	0,87	From figure 5
		CO_2(kg/s)		
		Air (kg/s)		
	Cooling Tower (3)	H_2O (kg/s)		299
	Turbine Seal Sytem (4)	H_2O (kg/s)		378
		CO_2(kg/s)		378
OUTLET	Stack Cooling Tower (2)	H_2O (kg/s)		323
		CO_2(kg/s)		323
		Air (kg/s)		323
	Main Condenser (5)	H_2O (kg/s)		341

Table 7. Input parameter for aftercondenser mass rate.

	Parameter		Mass rate (kg/s)
INLET	2nd outlet ejector (1)	H_2O (kg/s)	[Summation of PFF and SFF]
		CO_2(kg/s)	
		Air (kg/s)	
	Cooling Tower (3)	H_2O (kg/s)	[From Equation 5]
	Turbine Seal Sytem (4)	H_2O (kg/s)	0,15
		CO_2(kg/s)	$3{,}33\times10^{-2}$
OUTLET	Stack Cooling Tower (2)	H_2O (kg/s)	$3{,}33\times10^{-2}$
		CO_2(kg/s)	Same as 2nd outlet ejector mass rate
		Air (kg/s)	
	Main Condenser (5)	H_2O (kg/s)	[From Equation 6]

$$\dot{m}_{h2o(3)} = \frac{1}{h_{h2o(5)} - h_{h2o(3)}} \left(\dot{m}_{h2o(1)} \Delta h_{h20\,(1-5)} + \dot{m}_{co2(1)} \Delta h_{co2(1-2)} + \dot{m}_{udara(1)} \Delta h_{udara(1-2)} + \dot{m}_{h2o(4)} \Delta h_{h20\,(4-5)} + \dot{m}_{co2(4)} \Delta h_{co2(4-2)} - \dot{m}_{h2o(2)} \Delta h_{h20\,(2-5)}\right) \quad [7]$$

$$\dot{m}_{h2o(5)} = \dot{m}_{h2o(1)} + \dot{m}_{h2o(4)} + \dot{m}_{h2o(3)} - \dot{m}_{h2o(2)} \quad [8]$$

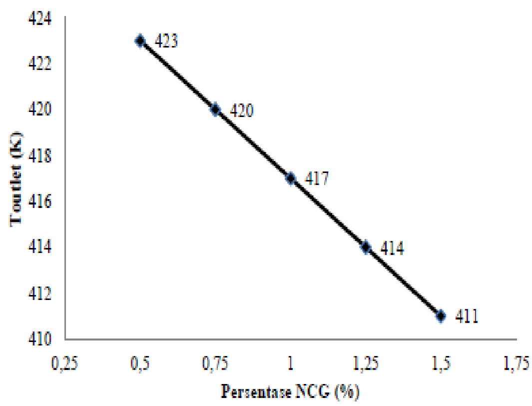

Figure 9. Second outlet ejector temperatures

COMPARATIVE ANALYSIS OF ATSR BETWEEN FREESTON METHOD AND NUMERICAL METHOD ON EJECTOR

To calculate using Freeston method, Eqs.[2]. and [3] are used and Figs. 2 and 3 are used to obtain correction factor of temperature and mass molecular. The ATSR from Freeston method on each NCG percentage is calculated using Eq. [2].

To obtain the result of ATSR simulation method, PFF from output of numerical simulation on each NCG percentage first is obtained. After that, using Eq.[2] ATSR number is obtained on each NCG percentage. After calculating with Freeston Method and simulating with numerical method, Tables 8 and 9 show the difference of both methods.

Table 8. Table of comparison of Freeston method and ATSR method in first ejector

NCG Percentage (%)	ATSR Freeston Method	ATSR simulation mehod	Error ATSR (%)
0,500	0,326	0,283	13,110
0,750	0,378	0,346	8,496
1,000	0,419	0,409	2,442
1,250	0,511	0,471	7,826
1,500	0,597	0,534	10,615
1,750	0,699	0,596	14,707
2,000	0,778	0,658	15,318
2,250	0,904	0,721	20,322
2,500	1,050	0,783	25,487
2,750	1,148	0,845	26,436
3,000	1,203	0,907	24,643
3,250	1,243	0,969	22,073
3,375	1,259	0,995	20,593

Table 9. Table of comparison of Freeston method and ATSR method in second ejector

Presentase NCG (%)	ATSR metode Freeston	ATSR metode simulasi	Error ATSR (%)
0,500	0,326	0,283	13,110
0,750	0,378	0,346	8,496
1,000	0,419	0,409	2,442
1,250	0,511	0,471	7,826
1,500	0,597	0,534	10,615

The average of ATSR error on first ejector is 16.31% and on second ejector is 17.6%. It means that the usage of Freeston method to calculate ATSR has no significant difference compared to calculation with numerical simulations to face all the possibilities in field.

RELATION OF NCG PERCENTAGE AND PFF MASS RATE

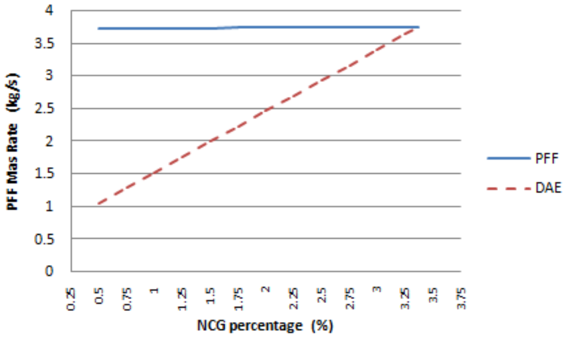

Figure 10. NCG Percentage vs PFF mass rate on first ejector

Figures 10 and 11 show the relation of increasing of NCG toward PFF mass rate needed to draw that NCG from condenser. With graphic relation, the PFF needed can be adjusted as saved steam from well depend on NCG percentage.

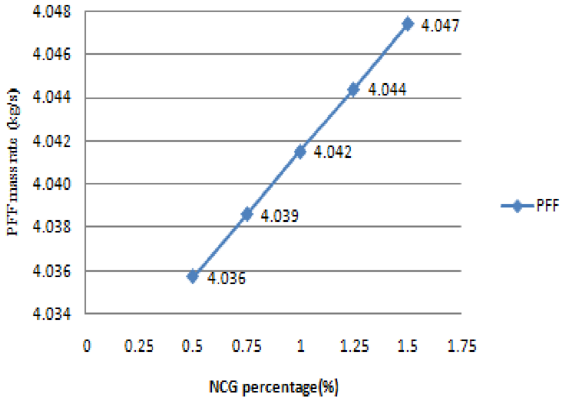

Figure 11. NCG Percentage vs PFF mass rate on second ejector

Equation 9 shows about the relation of NCG percentage and PFF mass flow rate for first ejector and Equation 10 shows about the relation of NCG percentage and PFF mass flow rate for second ejector. Figure 9 shows about the intersection of DAE equation and PFF equation to show limitation of NCG percentage variation so that ATSR will be not greater than 1. Figure 10 doesn't show DAE because the gradient of that line is small. Beside that, the information of intersection DAE line and PFF line in second ejector simulation graphic is unnecessary.

$$DAE = 0{,}938x + 0{,}584$$
$$PFF = 0{,}011x + 3{,}713 \quad [9]$$

$$PFF = 0{,}012x + 4{,}029 \quad [10]$$

ANALYSIS OF COOLING WATER MASS RATE AND CONDENSATE MASS RATE TOWARD NCG PERCENTAGE VARIATION IN INTER CONDENSER AND AFTERCONDENSER

Using Eqs. [5] and [7], Figures 11 and 12 are generated. These figures show the relation of the increasing of NCG percentage toward cooling water mass rate in intercondenser and aftercondenser.

Figures 11 and 12 show that the amount of cooling water will decrease proportionally with the increase of NCG percentage. It is due to the increase of NCG percentage (on fluid that leave from first ejector) makes that the amount of vapor on that fluid would decrease. The amount of cooling water to condense vapor will decreaseeither at intercondenser or at aftercondenser.

Using Eqs.[6] and [8], Figures 12 and 13 show that NCG percentage varies with condensate mass rateat both intercondenser and aftercondenser. Same case with mass cooling water used to condense vapor (shown in figure 10 and 12), condensate that will go out from intercondenser or aftercondenser to main condenser will decrease toward the increasing of NCG variation percentage. It is because vapor content in fluid from ejector decrease with the increasing of NCG variation percentage so that condensate which is yielded in intercondenser and aftercondenser will decrease as described in both figures.

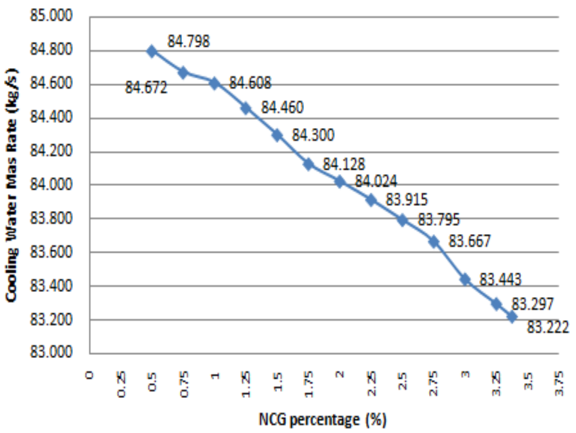

Figure 11. Relation of NCG percentage and usage of cooling water on intercondenser

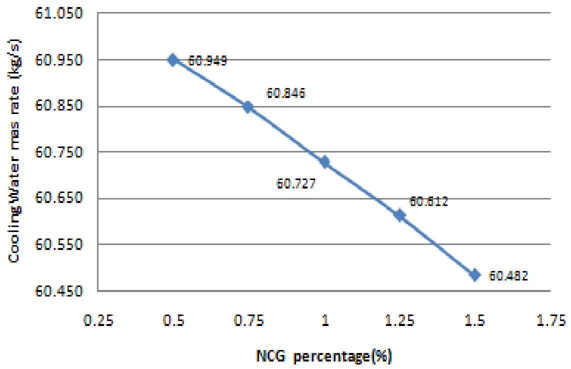

Figure 12. Relation of NCG percentage and usage of cooling water on aftercondenser

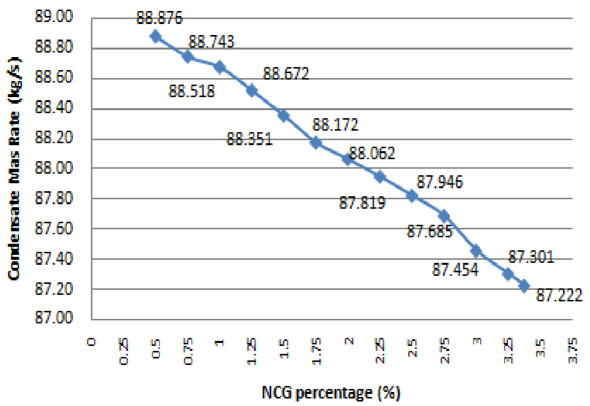

Figure 13. Relation of NCG percentage and condensate mass rate on intercondenser

CONCLUSIONS

The current study can be concluded as follow:

1. For the first and second ejector, the difference between results of Freeston method and computational simulation is about 16.31% and 17.60 % respectively.
2. PFF mass flow rates from computational method at first and second ejector for NCG content of 1.5% yield 3.73 and 4.047 kg/s respectively. When this flow rate is compared to actual data, there is saving of 1.70 and 1.82%.respectively
3. Water cooling mass flow rate of cooling tower to intercondenser and aftercondenser increases with the increase of NCG content to produce the equal steam mass flow rate to the second ejector (from interkondenser) and stack cooling tower (from aftercondenser)

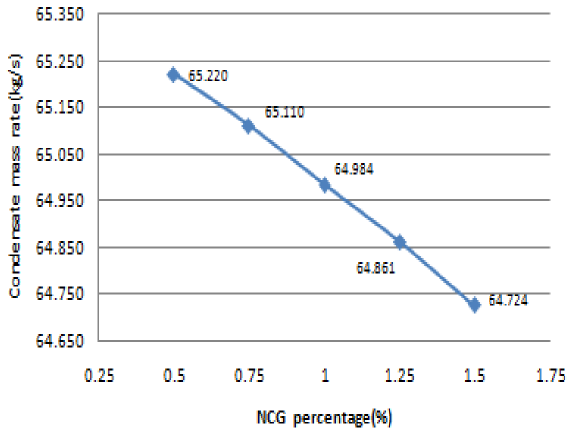

Figure 14. Relation of NCG percentage and condensate mass rate on aftercondenser

4. Condensate mass flow rate from after condenser and intercondenser to main condenser increases with the increase NCG content.

REFERENCE

[1] Freeston. D.H. *Geothermal Technology: Teaching the Teachers – Course Stage III*. Auckland University. 1996

[2] Al Habil, Akrimni. *Perbandingan Hasil Tes Performa dan Efisiensi Adiabatik Turbin Unit Satu Sebelum dan Setelah Perlakuan Overhaul Pada PLTP XXXX*. Laporan Kerja Praktek. ITB.2013

[3] Hasan, Muhammad. *Analisis Kinerja Ejektor Terhadap Kenaikan Persentase Gas Tak Terkondensasi Unit 1 dan 2 PLTP Gn. Salak*.Tugas Sarjana. ITB. 2007

[4] Kusumawardani, Putri. *Analisis dan Optimasi Sistem Ekstraksi Gas Pada Pembangkit Listrik Tenaga Panas Bumi*. Tugas Sarjana. ITB. 2012

[5] Fikri, Rausyan. *Analisis Performa Steam Jet Ejector Pada PLTP Studi Kasus PLTP XXXX*. Tugas Sarjana. ITB. 2012

[6] Millachine, Mauricio Andres Teke. *Guidelines for Optimum Gas Extraction System Selection*.Thesis.University Of Iceland. 2011

[5] AnsaldoEnerg ia, *XXXX Geothermal Powerplant Repowering*. 2001

[6] Subaid, Maria Sheryl. *Pengaruh Suhu Udara, Cuaca Hujan, Kelembaban Udara, dan Kecepatan Angin Terhadap Fluktuasi Konsentrasi Gas-Gas NO_2, O_3, dan SO_2, di Area PLTP XXX*. Tugas Sarjana. IPB. 2002