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Aquadest Production System as Steam Turbine Bottom Cycle III: Influence of Wastewater Percentage and Pinch Point Temperature Difference of Condenser

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Abstract. The needs for clean and safe water are growing as the population growing as well. This paper describes the variation of Wastewater Percentage and Pinch Point Temperature Difference (PPTD) on a 50 MW Steam Power Plant. After using the cooling water, not all water is discharged back to the sea, some of the water are used in throttling process where some of water will be vapor, and the other are merged with the water from water treatment and are going to be used for cooling cycle. It's found that by decreasing the condenser pressure from 8.45 kPa to 6.45 kPa it will produce vapor that could be condense into Aquadest with SEC (Specific Energy Consumption) at best condition as much as 697.85 kJ for producing 1 kg of Aquadest on PPTD 4.3 °C. On that condition, Aquadest could be produced at 0.0178 kg/s rate and the efficiency of turbine increase about 0.16%. Another benefit of this system is that this system discharges cooler water from the process, and has less impact to the environment.

NOMENCLATURE

X	The mass fraction (%)
h	Specific Enthalpy (kJ/kg)
m	Mass (Kg)
v	Specific volume (m^3/kg)
w_{net}	The network of the steam turbine (kJ/kg)
P	Power (kW)
p	Pressure (kPa)
q_{in}	Additional heat to the boiler (kJ/kg)
A	Additional variable (1)
B	Additional variable (2)
C	Additional variable (3)
COP	Abbreviation for Coefficient of Performance
EC	Abbreviation for Energy Consumption (kW)
SEC	Abbreviation for Specific Energy Consumption (kJ/kg)
η_{th}	Power plant efficiency, %
AP	Aquadest Production (kg/s)
T	Temperature (°C)

SUBSCRIPT

C1	Cooling fluid from water treatment
C2	Cooling fluid from pump merged with cooling water from water treatment and then heading to the condenser
C3	Cooling fluid after condensation process
C4	Cooling fluid inside water tank, result from throttling process and merging with cooling fluid from water tank
aq	Abbreviation for Aquadest
f	Fluid
g	Gas
f g	Fluid and Gas
t5	Working fluid flowing to turbine
t6	Working fluid flowing to condense

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INTRODUCTION

Sanitation and neat environment is very important for our living. Around 88% of children's death were caused by Diarrhea. In Indonesia Diarrhea is still the main cause of the death of children under five years old [1]. This won't have to occurred if people realized how important it's to keep our environment clean and neat so that the water around environment is clean as well. Today, 1 in 9 people lack access to safe water, 1 in 3 people lack access to a toilet, and more people have a mobile phone than a toilet [2]. In order to overcome this problem, engineers are trying to produce fresh water from sea water, since over 96% percent of water in Earth's surface is saline water in the oceans, while the rest is mainly in Lakes, Rivers, Glaciers. Giving only 0.76% of water in the world that human could use [3].

There are already some technologies to convert sea water to fresh water. For example, seawater desalination by utilizing solar energy still. This solar operation is managed by heat and mass transfer occurring in the system. Inside the solar still, the convection heat and mass transfer are moving from the water surface to inside the glass cover trapping the long wave radiation and heats up the water by using the "greenhouse" method, the water evaporates and condenses on the cover. [4]. Another example is water purification technology using magnetic assistance, this method is adapted from ore mining industries to anti scale-treatment [5]. There are also some methods of desalination aside from purification, such as desalination process by pervaporation using hydrophilic molecule polyether membrane [6]. Desalination is also able to achieve by using hydrate process. This desalination method is done by using diagramite to assist cyclopentane process at atmospheric pressure. Although this method is cheap and easy, because of the limited mass transfer under constant state enormously hinders the growth of hydrate, causing only small percentage of conversion [7]. A lot of methods of desalination is being on research right now, including the research to improve desalination technology, such as in a method of salt remove capacity (SRC) by using the carbon electrodes in a membrane capacitive deionization (MCDI), the needed enhancement for SRC before applying MCDI is critical to the process [8]. Desalination technology is already being a potential market in the future, and solar thermal-powered desalination is one of the most viable solution right now [9]. The traditional way of doing desalination isn't only energy intensive but also not eco-friendly. Innovation is made in order to avoid that such as using multi effect desalination system operated by using ocean thermocline energy [10].

This paper describes the simulation tool for generating Aquadest. The method and process of this research is a new innovation which is utilizing the waste of warm water condenser output of the steam power plant. Generally, this warm water is directly being discharged into the sea after process without being used. Warm sea water is harmful for environment. The evolution of a stable marine habitat is dependent upon myriad factors, including water temperature. If an ecosystem becomes warmer, it can create an opportunity where outside species or bacteria can suddenly thrive where they were once excluded. This can lead to forced migrations and even species extinctions [11]. In this simulation some of hot water waste is flowed back into the system by conducting throttling process, so the warm water phase could change into water vapor and then could be condensed into Aquadest. Aquadest production is different from desalination water production because of the Aquadest production using the phase change of water so the result from condensed water vapor should be really pure. Another advantage is this tool could produce Aquadest with a very low cost. Adding this tool to the steam power plant does not give drawback to the system, in fact changing in the condenser pressure will increase the power generated from power plant [12]. Using this tool also could lower the temperature of waste water into the sea, so it should be eco-friendlier.

This simulation can be done with many variations such as variation with vacuum condenser to increase turbine power [12]. Variation of pinch point temperature difference (PPTD) to optimize condenser performance [13], variation in the amount of water directly discharged into the sea, as well as variation in water pressure within the cold-water container tube to improve the efficiency of the production of Aquadest and thermodynamic efficiency [14]. This paper only talks about variation on the amount of waste water discharged into the sea, and the pinch point temperature difference (PPTD).

METHODS

After being used in condenser, some of the used cooling water will not be directly discharged into the sea but will go to the throttling valve. In throttling process, also some of the used cooling water will expand and lose its pressure, decrease its saturation temperature following the pressure. While the small portion of used cooling water in throttling valve will be vapor, this water vapor could be condensed and producing Aquadest, and the other portion of used cooling water will be flowed back into the system and merge with the water coming from the sea and be used for another condensation process. This process will occur over and over again.

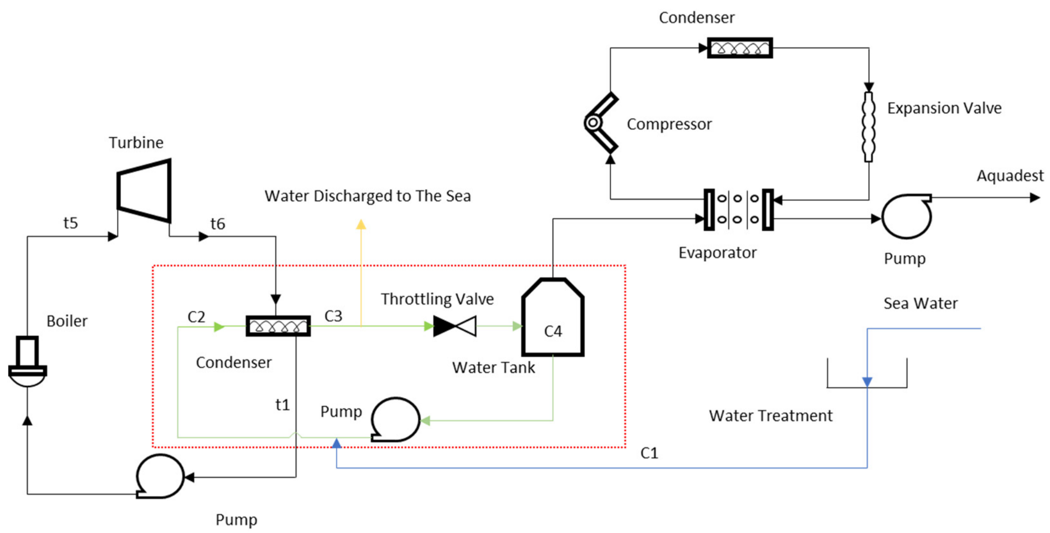

FIGURE 1. Schematic Diagram of throttling process in sea water condenser power plant

While the process occurs over and over again, this paper will describe the influences of variation in percentage cooling water discharged and pinch point difference of condenser to the whole system, especially the produce rate of Aquadest and the efficiency of steam power plant.

TABLE 1. Calculation Results

Parameter	Value
T_{t5} (Turbine Temperature)	510 °C
p_{t5}	8900 [kPa]
$s_{turbine}$	6.696 [kJ/kg.K]
$\dot{m}_{cooling\ water}$	148.13 kg per 1 kg working fluid
$p_{condenser}$ (pressure)	8.45 [kPa]
$\eta_{isentropic}$ (efficiency)	87%
η_{th} (efficiency of steam power plant)	34.99%
power plant)	33.7 °C
PPTD	9.2 °C

There are consequences of changing the pressure of the condenser, such as achieving lower temperature. At 8.45 kPa, the saturated temperature is around 42.6 °C while, on 6.45 kPa the temperature could be lowered to 37.5 °C, which will lead to less harmful to the environment for discharged water heading back to sea. Another consequence is that this change could lead to produce additional energy for turbine.

After all the variables are known, now moving to the calculation. The first thing to calculate is the mass fraction of vapor, by using the equation below.

$$Xvapor = \frac{h_{c3} - h_{f\,c4}}{h_{f\,g\,c4}} \quad (1)$$

And then the next step is to calculate the mass of cooling water entering the condenser by using the next equation, note that, A, B and C are additional variables.

$$m_{c2} = \frac{q_{in}}{C} \quad (2)$$

$$C = h_{c3} - A \times h_{f\,c2} - B - (1 - A) \times h_{c1} \quad (3)$$

$$A = \frac{(1 - \%discharged) \times (h_{g\,c2} - h_{c3})}{h_{f\,g\,c2}} \quad (4)$$

$$B = v_{c2} \times (101.325 - p_{c2}) \quad (5)$$

By knowing the mass of cooling water entering the condenser, then it's able to find the water mass heading to the condenser by using the equation below.

$$m_{c4} = m_{c2} \times A \quad (6)$$

Then moving on to the mass of water discharged, the value of this calculation is depending on the value of variation percentage water discharged back into the sea.

$$m_{discharged} = \%\, discharged \times m_{c2} \quad (7)$$

The power of pump in order to push the cooling fluid from water tank and merge with the cooling fluid from the water treatment is proposed with the equation below.

$$P_{pump\;C4} = v_{c2} \times m_{c4} \times (101.325 - p_{c4}) \quad (8)$$

While the mass of Aquadest, the result from small portion of throttling process that became a vapor is proposed by the equation below.

$$m_{aq} = \frac{Xvapor \times m_{c4}}{(1 - X_{vapor})} \quad (9)$$

To calculate the additional cooling water mass, the equation is proposed below.

$$m_{c1} = m_{c2} - m_{c4} \quad (10)$$

Next is to calculate the power to condense the vapor into Aquadest by using the equation below, note that the value of *COP* is assumed.

$$P_{comp} = \frac{m_{aq} \times h_{f\,g\,c2}}{COP} \quad (11)$$

After is to calculate the total energy to produce Aquadest with the equation below.

$$EC = P_{pump} + P_{comp} \quad (12)$$

In order to calculate the efficiency of the power plant, Specific Energy Consumption (SEC) is needed, below is the equation proposed to calculate SEC to produce 1 kg Aquadest.

$$SEC = \frac{EC}{m_{aq}} \qquad (13)$$

The final is to calculate the power plant efficiency, with the influences of using throttling process and producing Aquadest, with the formula proposed below.

$$\eta_{th} = \frac{(w_{net} \times \dot{m} - EC - P_{pump})}{q_{in}} \qquad (14)$$

RESULT AND DISCUSSION

This simulation varies the PPTD and the percentage of discharged water mass, with the condenser pressure lowered from 8.45 kPa to 6.45 kPa to optimize the power of the turbine, and also the pressure of the cooling water storage tube is maintained at 4.22 kPa. From this simulation, the best results were obtained when the amount of distilled water produced with the SEC was negative, the amount of cooling water added from the sea was not much different from the reference point design of the power plant, and with turbine efficiency higher than the reference power plant design point, with results calculation as seen in Table 2.

TABLE 2. Results of Calculation

Parameter	Value
T_{t5}	510 ^{o}C
p_{t5}	8900 [kPa]
$s_{turbine}$	6.696 [kJ/kg.K]
T_{t6}	37.5 ^{o}C
p_{t5}	6.45 [kPa]
$T_{condenser}$	37.5 ^{o}C
$P_{condenser}$	6.45 [kPa]
T_{pump}	37.5 ^{o}C
P_{pump}	8900 [kPa]
$\dot{m}_{working\ fluid}$	1 [kg/s]
T_{C1}	30 ^{o}C
$\eta_{isentropic}$ (efficiency)	87%
$q_{in\ from\ boiler}$ (heat in)	3255.3 [kJ/kg]
$w_{Turbine}$ (turbine energy)	1167.79 [kJ/kg]
$q_{out\ at\ condenser}$ (heat out)	2087.478 [kJ/kg]
w_{pump} (work of pump)	8.98 [kJ/kg]
$W_{netto\ turbine}$	1158.82 [kJ/kg]
$p_{water\ tank}$	4.22 kPa
PPTD	4.3 □C
% discharge	98 %
X_{vapor}	0.0058
m_{C2}	153.11 [kg/s]
m_{C4}	3.04 [kg/s]
$m_{discharged\ water}$	150.05 [kg/s]
$P_{pump\ C4}$	0.29 [kW]
m_{aq}	0.0178 [kg/s]
m_{C1}	150.07[kg/s]
P_{compp}	43.33 [kW]
EC	-12.44 [kW]
SEC	-697.85 [kW/s]
$\eta_{th\ new}$	35.15%

From the data, it could be seen that this tool is capable of producing distilled water at 0.0178 kg/s rate, with the energy required about 12.44 kW and increasing the efficiency of power plant by 0.16%. Below is the diagram for all simulation sequences:

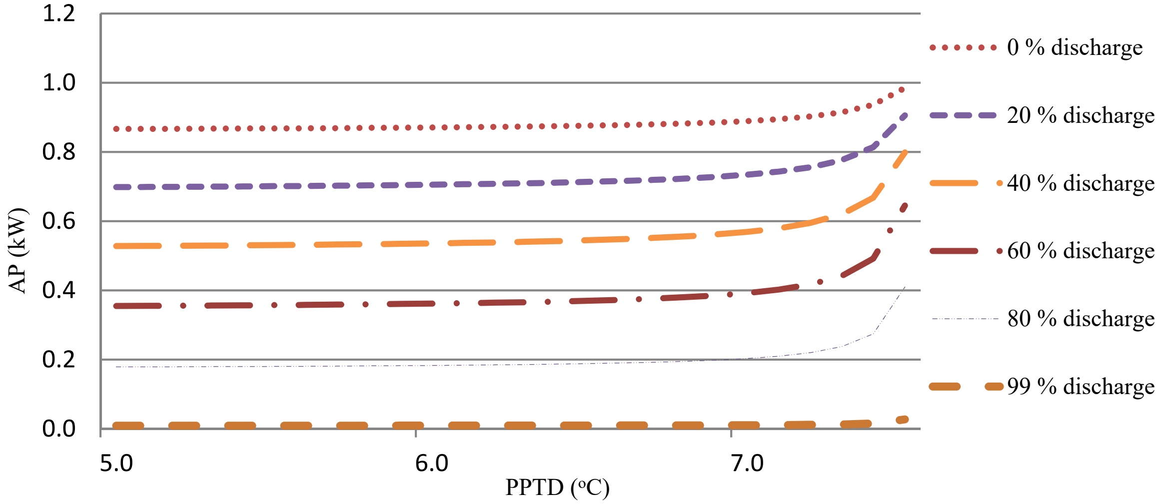

FIGURE 2. PPTD vs AP Diagram

On the diagram above, it is able to say that the PPTD 0-7 ˚C has AP which is increasing with a slight increase and the diagram looks like a straight line, while for PPTD values above 7 ˚C it has AP which has a significant increase.

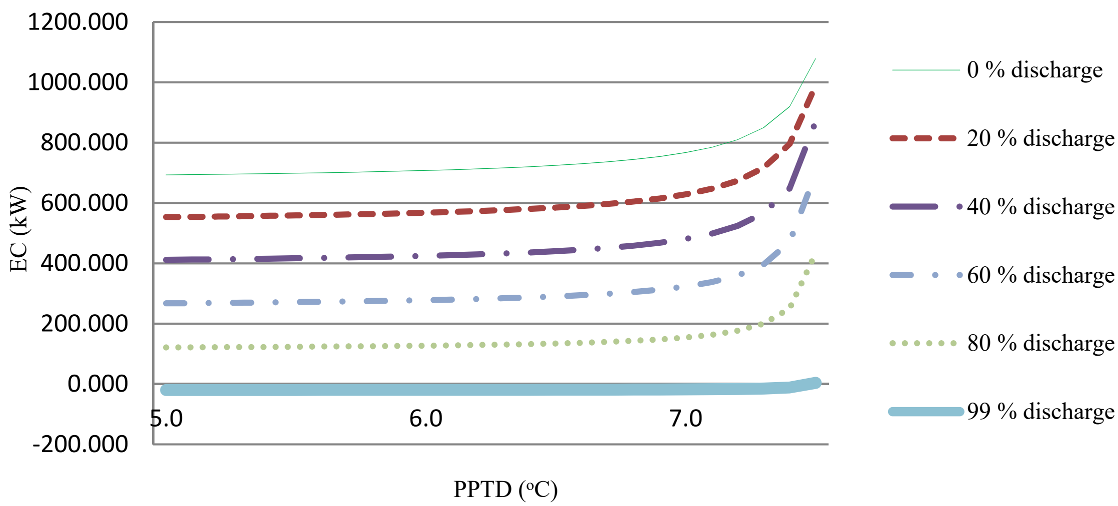

FIGURE 3. PPTD vs EC Diagram

On the diagram above it can be seen that at the condition of discharged water between 0-90% has a positive EC in all variations of PPTD. This shows that to produce distilled water, additional energy is needed beyond the excess energy produced by the power plant with new conditions in the simulation. Whereas for the percentage of discharged water at 99% has a negative value for EC at PPTD 0-7.4 ˚C. This shows that to produce distilled water, there is still an excess power plant in the new condition in the simulation compared to the design point conditions.

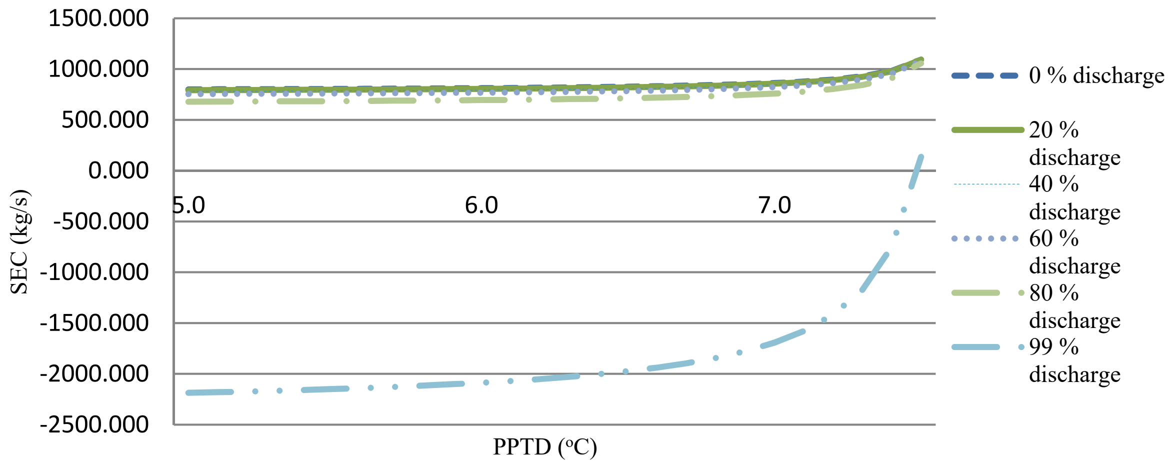

FIGURE 4. PPTD vs SEC Diagram

On the diagram above it can be seen that for the percentage of discharged water between 0-90% the value of SEC is above 0 and the diagrams are close and tight to each other, on the other hand the percentage of discharged water at 99% has a negative value of SEC for PPTD 0-7.4 ˚C with the value far below 0. This negative SEC is the expected result from this simulation and this negative SEC condition is a benefit condition. Below is the diagram of simulation for percentage of water discharged at 90% to 99%, in order to get detail results from this simulation:

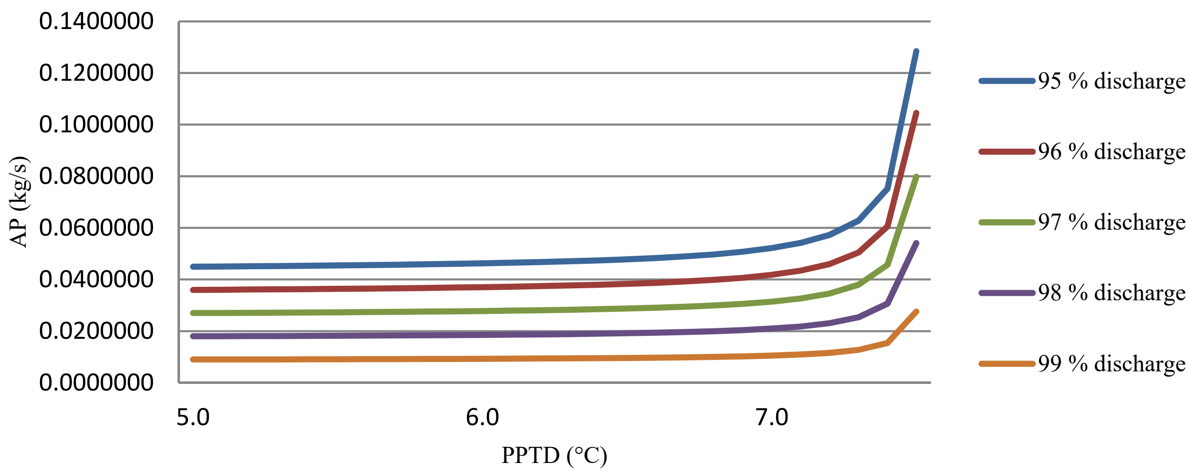

FIGURE 5. PPTD vs AP Diagram

There are reasons why the value is negative at specific parameter, by using the used cooling water to throttling valve, the temperature of cooling water could be lowered because of saturation condition, while some of the water are changing to vapor and will be evaporated on evaporator. From the diagram, the more discharged lead to lower energy, and some of them are negative. This means there are exceeds energy which is a surplus while discharging the water.

From the results, all conditions have positive values, it means that all conditions from 90% to 99% are able to produce Aquadest.

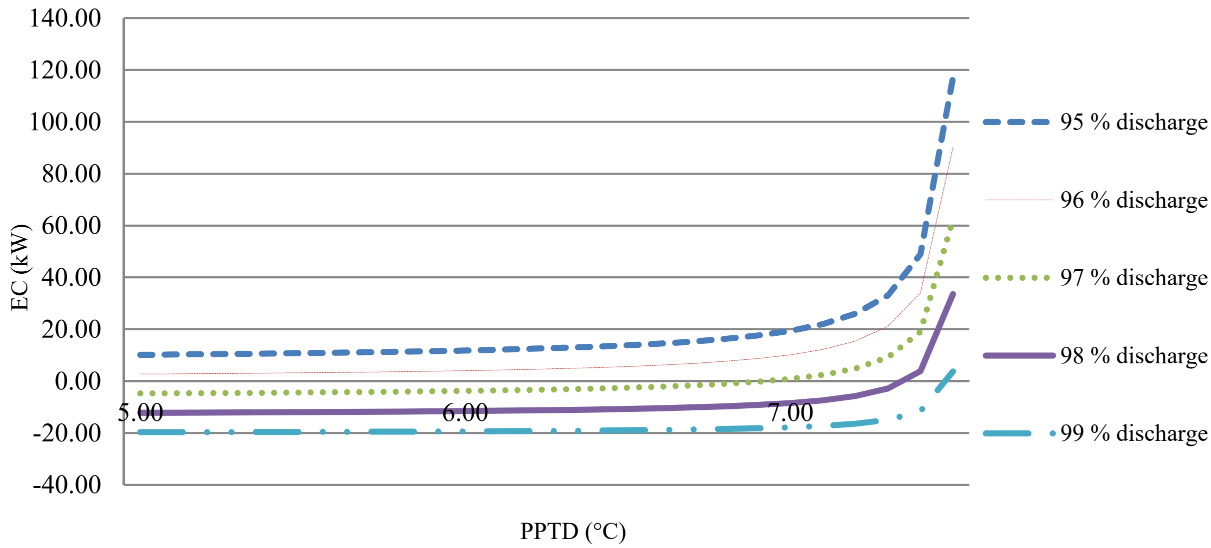

FIGURE 6. PPTD vs EC Diagram

On the diagram above it can be seen that for the percentage of 97%, 98%, and 99%, it has a value under 0. It means that the additional energy needed to produce distilled water is negative. While the percentage of waste water below 97% has a positive EC, meaning that the excess power of the turbine produced still requires additional energy.

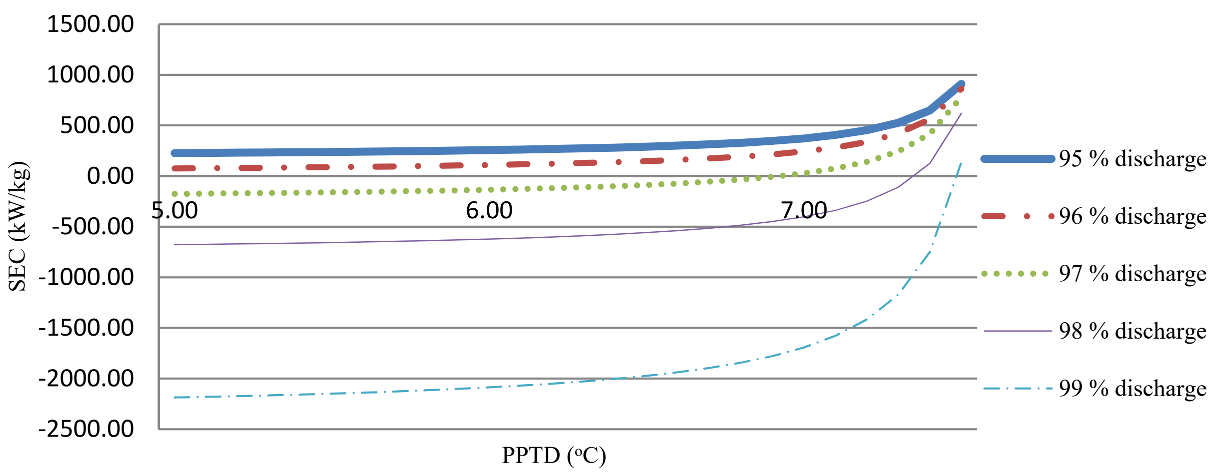

FIGURE 7. PPTD vs SEC Diagram

On the diagram above it can be seen that the SEC value for the percentage of 97%, 98%, and 99%, is negative, and also for the percentage of 99% having a diagram far below 0. This shows that in order to produce distilled water it still leaves the turbine additional power from excess power turbine with a new design in simulation compared to design points. While the percentage of wastewater below 97% has a positive SEC.

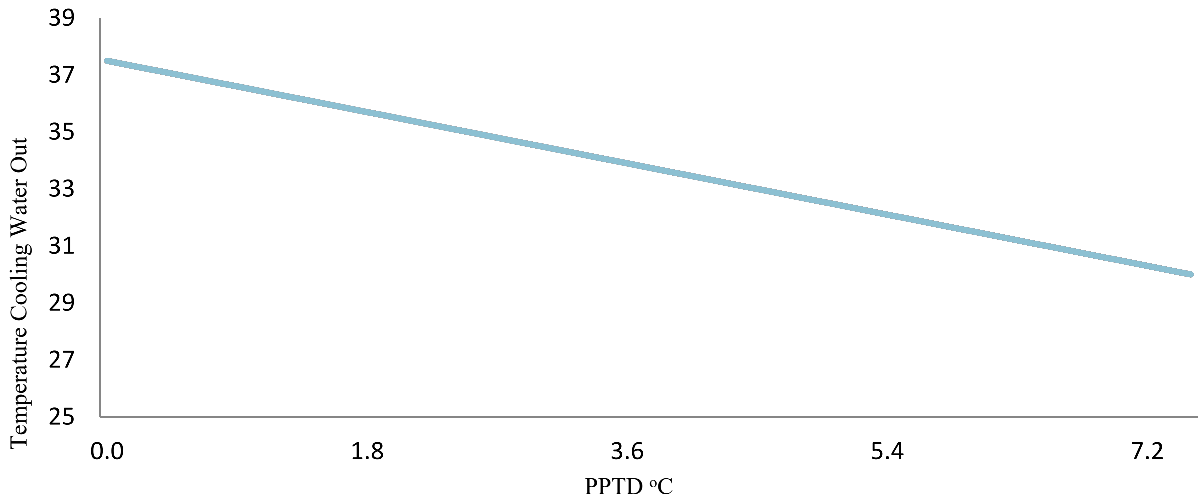

FIGURE 8. PPTD vs Discharged Water Temperature Diagram

Since the temperature of cooling water heading back to the sea are influenced by the working fluid temperature steam power plan heading to condenser and pinch point, so that the values are identical for all variation. This simulation is using maintained or fix value for the temperature of working fluid heading to condenser, so the temperature of cooling water only could be influenced by the value of PPTD.

From all simulations from Figure 2-7, it can be seen that the greater the PPTD, the greater also for the AP, EC, and SEC. Whereas the greater the percentage of water discharged, the smaller the AP, EC, and SEC.

CONCLUSION

1. By using, *throttling process* on cooling water before getting to condenser on powerplant and the pressure of condenser decreased from 8.45 kPa to 6.45 kPa, will produce vapor that could be condense into Aquadest with SEC (*Specific Energy Consumption*) at best condition as much as 697.85 kJ fir producing 1 kg of Aquadest on PPTD 4.3 °C.
2. On that condition, Aquadest could be produced at 0.0178 kg/s rate and the efficiency of turbine increase about 0.16%.
3. The greater value of PPTD then, the greater value also for SAP, EC and SEC, on the other hand the smaller the value of water discharged, the smaller the value of SAP, EC, and SEC.
4. Producing less harmful discharged water to the environment.

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