Effect of brine mass rate on pressure drop and dirt factor in evaporator design

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Abstract. Geothermal is one of the most significant natural resource potentials in Indonesia. One power plant that utilises geothermal steam as its energy source is PLTP. Geothermal steam that has passed through the geothermal power plant separator to move the turbine while the residual waste (brine) with a high enough temperature has the potential to be a source of heating to produce electrical energy in the Kalina cycle generator. Using brine, before entering the turbine, it must first become airtight in the evaporator. Evaporator design requires initial parameters namely brine fluid flow rate and ammonia-water flow rate, shell dimensions and tube dimensions as well as the number of passes, then performs the design calculation steps until the calculation results meet operating requirements, namely the pressure drop value and the dirt factor. Different variations of brine rate will produce different pressure drops and soil factors. Brine rate variations are 11 kg/s, 22 kg/s, 33 kg/s, 44 kg/s, 55 kg/s and 66 kg/s show the lowest pressure drop of 0.098 bar and the most massive 0.68 bar, and the smallest dirt factor is 0,002 (hr)(m² oC)/Joule moreover, the largest is 0,00019 (hr)(m² oC)/Joule.

1. Introduction
Organic Rankine Cycle (ORC) is a well established technology for power generation from low grade heat sources, including waste heat [1-3]. This cycle comes from a heat source (waste brine) that comes out of the PLTP separator then enters through the evaporator. The working fluid uses an ammonia-water mixture from a regenerator that is heated using waste brine heat [4]. The evaporation process takes place in the evaporator from a saturated liquid condition to a two-phase or wet vapour condition. Evaporator here has a crucial role in the success of this cycle so that the evaporator design must meet operative requirements. The design steps must consider the preheating area and the evaporation area. The novelty of the Evaporator Design here is to use variations in the brine fluid flow rate and a mixture of 20 % water and 80% ammonia, which affects the pressure drop and dirt factor so that it can determine the best Evaporator operation by flowing the brine with the right flow rate.

2. Evaporator design methods
The evaporator design research method is varying the brine flow rate at 11 kg/s, 22 kg/s, 33 kg/s, 44 kg/s, 55 kg/s and 66 kg/s and the mixture of 20 % water and 80% ammonia flow rate at 16.5 kg/s. A brine is a hot fluid that enters at a temperature of 175 and exits at a temperature of 110 through a tube of 19.05 mm in diameter, and an ammonia-water mixture is a cold fluid that enters at a temperature of 60 and exits at a temperature of 105 through a shell diameter of 736.6 mm. The design of the evaporator must go through the stages of designing the evaporator, which is as follows:
Calculation of Preheat Zone Heat Transfer Rate. Preheat zone heat transfer rate was computed using [5] Eq. (1).

\[ (q_p) = \dot{m}_{wf} \times (h_{f\text{ out}} - h_{f\text{ in}}) \]  

(1)

Where \((q_p)\) is preheating zone heat transfer rate (W); \(h_{f\text{ out}}\) is enthalpy liquid in Tc out (kJ/kg); \(h_{f\text{ in}}\) is enthalpy liquid in Tc in (kJ/kg); \(\dot{m}_{wf}\) is mass flow of working fluid (kg/s)

Evaporation Heat Zone. Heat rate was computed using Eq. (2).

\[ (q_v) = \dot{m}_{wf} \times (h_{g\text{ out}} - h_{f\text{ in}}) \]  

(2)

Where \((q_v)\) is evaporation heat transfer rate (W); \(h_{g\text{ out}}\) is vapour enthalpy in Tc out (kJ/kg)

Calculation of heat balance based on heat/heat needed in the evaporation process. The calculation uses equation 3-5 below:

\[ Q_{\text{evaporator}} = (q_p) + (q_v) \]  

(3)

\[ Q_{\text{brine}} = \dot{m}_{\text{brine}} \times C_p \times \Delta T_{\text{panas}} \]  

(4)

\[ Q_{\text{brine}} = Q_{\text{evaporator}} \]  

(5)

Where \(C_p\) is type of heating fluid (water) (kJ/kg °C); \(Q_{\text{evap}}\): evaporator heat (kW); \(Q_{\text{brine}}\): hot brine (kW); \(\dot{m}_{\text{brine}}\): brine mass flow (kg/s)

Temperature Difference in the heat with hot fluid to the outside. The \(\Delta t_{\text{LMTD}}\) calculation uses [6] the following equation (6):

\[ \Delta t_{\text{LMTD}} = \left( \frac{\Delta T_{\text{in}} - \Delta T_{\text{out}}} {\ln \left( \frac{\Delta T_{\text{in}} + \Delta T_{\text{out}}}{\Delta T_{\text{in}} - \Delta T_{\text{out}}} \right)} \right) \]  

(6)

Where \(\Delta t_{\text{LMTD}}\) is Logarithmic Mean Temperature Difference (°C).

Weight Temperature. Calculation of Weight Temperature uses the equation below:

\[ \Delta t_{\text{weight}} = \frac{Q_{\text{evaporator}}}{\Delta t_{\text{LMTDp}}} - \frac{Q_{\text{vaporisation}}}{\Delta t_{\text{LMTDv}}} \]  

(7)

Where \(\Delta t_{\text{LMTDp}}\) is Logarithmic Mean Temperature Difference zone preheat (°C); \(\Delta t_{\text{LMTDv}}\) is Logarithmic Mean Temperature Difference zone vapourisation (°C)

Determination of the diameter of the tube (shell), the number of pipes (tube), and the dimensions of the evaporator using the underlying assumptions of the TEMA (Tubular Exchanger Manufacturers Association).

The Surface Area of a Submerged Shell. Calculation of the number of shell in the evaporator zone uses the equation below:

\[ a's = C_1 \times ID_{s}^2 \]  

(8)

Where \(a's\) is surface area of a submerged shell (m²); \(C_1\) is tube factor; \(ID_{s}\) is inner diameter of the shell (m).

The Number of Tube Preheat Zones. Calculation of tube preheat zones uses the equation below:

\[ N_{tp} = N_{t} \times \frac{ar's}{\pi \times ID_{s}^2} \]  

(9)
Where $N_{tp}$ is Number of preheating zone tubes; $n$ is number of passes tubes; $N_T$ is the total number of tubes. The Number of Tube Vaporization Zones. Calculation of tube vaporization zones uses the equation below:

$$N_{tv} = N_T - N_{tp} \quad (10)$$

The Surface Area on the Side of the Shell. The calculation of the surface area uses the following equation:

$$a_s = \frac{ID \times C'B}{Pt \times 144} \quad (11)$$

Where, $a_s$ is shell surface area ($m^2$); ID is inner diameter of the shell (m); $C'$ is clearance between the sides of the tube (m); B: baffle space (cm); Pt: pitch or the distance between the midpoints of the tube (m).

Calculate the speed of fluid flow. Calculation of refrigerant fluid flow velocity uses the following equation:

$$G_s = \frac{w}{a_s} \quad (12)$$

Where, $G_s$ is refrigerant fluid flow velocity on the shell side (kg/s m$^2$); $w$ is weighed flow or mass flow of brine fluid (kg/h)

Determine the Reynolds Number Value on the Side of the Shell. The calculation of Reynold numbers in the shell uses the equation:

$$Re_{shell} = \frac{D \mu_s}{\nu_s} \quad (13)$$

Where $Re_{shell}$ is Reynold value for heat transfer in the shell; $\nu_s$ is viscosity value in shell (kg/m s)

Determine the heat transfer coefficient on the side of the shell. Calculation of heat transfer coefficient using the equation:

$$h_o = jH \left( \frac{k}{\nu_s} \right)^{1/3} \quad (14)$$

Where, $h_o$ is heat transfer coefficient on the shell side (W/(m$^2$ °C); $jH$ is a factor for heat transfer [7]; $k$ is thermal conductivity on the shell side (W/(m °C)

Calculation of Brine Fluid Heat Transfer on the Tube Side. Tube Calculation of surface area using the equation:

$$a_t = \frac{M!}{3} \quad (15)$$

Calculations for flow rates, Reynold numbers and heat transfer coefficients use the same equation as the shell section. The design of the Evaporator Zone is divided into two zones, namely the preheat zone and the vaporisation zone.

Preheat Zone. Calculation of clean overall coefficient preheat zone value using the equation:

$$U_p = \frac{h_o \times h_o}{h_o + h_o} \quad (16)$$

Where $U_p$ is clean pipe heat transfer coefficient preheat zone, (W/(m$^2$ °C); $h_o$ is overall heat transfer coefficient of the tube (W/(m$^2$ °C); $h_{op}$ is heat transfer coefficient on the shell side of the preheat zone (W/(m$^2$ °C)

Vaporation Zone. Calculation of clean overall coefficient evaporation zone value using the equation:

$$U_v = \frac{h_o \times h_{ov}}{h_o + h_{ov}} \quad (17)$$
Where, \( U \) is Heat transfer coefficient of the clean pipe vaporisation zone (W/(m\(^2\) °C)); \( h_o \) is the overall heat transfer coefficient of the tube (W/(m\(^2\) °C)); \( h_{ov} \) is heat transfer coefficient on the shell side of the zone (W/(m\(^2\) °C))

**Calculation of the total heat transfer area of the evaporator.** The preheat zones using the equation:

\[
A_p = \frac{\dot{q}_p}{U_p \Delta t} \tag{18}
\]

**Calculation of the total heat transfer area of the evaporator.** The evaporation zones using the equation:

\[
A_v = \frac{\dot{q}_v}{U_v \Delta t} \tag{19}
\]

Where, \( A_p, A_v \) is extensive preheat, evaporation heat transfer area, m\(^2\); \( \dot{q}_p, \dot{q}_v \) is preheated, evaporation heat transfer rate, W; \( U_p, U_v \) are clean transfer pipe coefficient preheat, evaporation zone, (W/(m\(^2\) °C))

**Clean Overall Coefficient.** Calculate the clean overall coefficient value using the following equation:

\[
U_c = \frac{\sum UA}{A_p + A_v} \tag{20}
\]

Where \( U_c \) is coefficient of overall heat transfer condenser (kW/m\(^2\) °C).

**Dirt Overall Coefficient.** Calculate the dirt overall coefficient value using the following equation:

\[
U_d = \frac{Q_{evaporator}}{A \times \Delta t} \tag{21}
\]

Where \( U_d \) is coefficient of overall heat transfer condenser (kW/m\(^2\) °C).

**Calculating Dirt Factor.** The dirt factor value is calculated using the following equation:

\[
R_d = \frac{(U_c - U_d)}{(U_c \times \Delta t)} \tag{22}
\]

**Pressure drop.** Calculation of \( \Delta P \) on the shell side uses the following equation:

\[
\Delta P_s = \frac{f \times G_r^2 \times ID_{shell} \times (N+1)}{5.22 \times 10^{10} \times De_{shell} \times s \times \phi s} \tag{23}
\]

**Pressure drop.** Calculation of \( \Delta P \) on the tube side uses the following equation:

\[
\Delta P_t = \frac{1}{2} \times \frac{f \times G_r^2 \times LN}{5.22 \times 10^{10} \times De_{tube} \times s} \tag{24}
\]

### 3. Results and discussion

Brine is a heating liquid that comes from residual geothermal steam that has passed through the separator of the Geothermal Power Plant. Brine can affect the increase in mass flow rate or decrease in mass flow rate, which changes will have an impact on the generating system itself as well as on the performance of the evaporator [8]. Figure 1 shows the results of the design where the effect of variations in the mass flow rate of brine to the pressure drop on the shell side. Figure 2 shows the results of the design where the effect of variations in the mass flow rate of brine to the pressure drop on the tube side. Figure 3 shows the results of the design where the influence of brine mass flow rate on the fouling factor.
These changes can be seen in figure 1 which shows that the higher value of the mass flow rate of the brine can cause an increase in the value of the pressure drop both the shell side (ammonia-water fluid) and the tube side (brine). Figure 2, which shows that the higher the value of the brine mass flow rate, the fouling factor evaporator value shows a decrease. The brine mass flow rate is higher than ammonia-water mass flow rate, then the mass flow rate of ammonia-water fluid will also be higher, both changes in mass flow rate will affect the amount of fluid flow velocity on the shell side (ammonia-air) and the tube side (brine). A low fluid flow rate will cause a higher pressure drop. The highest value of pressure drop that meets the design requirements for a mixture of water-ammonia through the tube is 0.68 bar and the pressure drop on the side of the tube (salt water) is 0.23 bar. The most operative result is a pressure drop of 0.68 with a ammonium-water flow rate of 66 kg/s because it approaches the operating requirements of 1 bar. The result of this pressure drop is in accordance with the results of the shell and tube type heat exchanger analysis [9]. Changes in the brine mass flow rate can also affect the value of the fouling factor of the evaporator. When the value of mass flow brine decreases, the value of fluid flow velocity will decrease so that the value of the fouling factor is higher. A good fouling factor value for a heat exchanger must be greater or equal than the standard value of 0.002 m$^2$°C/W. The best result of dirt factor is 0.0019 m$^2$°C/W at the brine flow rate of 44 kg/s, this is in accordance with the investigation of dirt factors [10]. If the fluid flow velocity is small it will cause a higher pressure drop resulting in decreased performance of the heat exchanger. The fouling factor value that is smaller than the minimum standard is also not good for the evaporator, because when the brine mass flow rate is higher causing the fluid speed will be faster this causes the dirt rate on the evaporator will be faster so that the ability to resist the formation of dirt or to scale on the evaporator is getting reduced.
4. Conclusions
Conclusions from the design of shell and tube type Evaporator based on design data and the results of the analysis that have been carried out include:

- The heat transfer rate generated by the Evaporator is 74,243,400.9 W.
- The results of the Evaporator calculation obtained the value of dirt factor ($R_D$) of 0.0019 m$^2$oC/W at a brine mass flow rate 44 kg/s.
- A pressure drop on the side of the shell (ammonia-water) at 0.68 bar at a mass flow rate of 66 kg/s and a pressure drop on the side of the tube (brine) of 0.23 bar at a mass flow rate of 66 kg/s.

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