Geothermal Steam Water Separator Sizing for Optimizing Power Plant Cost

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ABSTRACT

One of the steps in flash geothermal power plant design is determining a suitable separator size based on the chosen separator type. There are two main types of separators: horizontal and vertical separators. The challenge is how to decide the proper type and the optimum size. The choice of the separator type normally depends on the developer preference and experience. However, this choice will affect the investment cost of the separator in each project. The smaller size of separator requires less material therefore lower the cost. It simplifies fabrication as well as easy delivery and site installation.

The main parameters for designing the separator are geothermal fluid enthalpy, mass flow rate and operating pressure. Five different reported models were used to calculate, the vessel diameter, separator length, vessel surface area and vessel volume. The modeling did not consider the pressure drop within the separator or separator efficiency.

Several simulations were conducted to understand how the input parameters affect the separator sizing. Actual field data were used to validate the result.

1. NTRODUCTION

Most conventional geothermal resources are liquid dominated (DiPippo, 2012). The most important consideration when developing liquid dominated reservoirs is to separate the two-phase fluid mixture into steam and water to provide a high-quality steam for the steam turbines. Low quality steam can damage the steam turbine decreasing its life and resulting in loss of power generation. At the same time, water droplets carried with the steam may contain minerals that can cause scale deposition on the blades, casing and nozzles, decreasing the turbine efficiency (Zarrouk & Moon, 2014). Separators are commonly classified into two common designs: horizontal and vertical separators. Vertical separators are recommended for a high vapour/liquid ratio (high enthalpy), while horizontal separators are used mainly for separating vapour from the fluid mixture with low vapour/liquid ratio (Svreck & Monnery, 1993). Horizontal separators rely on gravity settling as the separation mechanism, while vertical separators are based on centrifugal force and fluid agglomeration (Zarrouk & Purnanto, 2014). The separator sizing is important when selecting a suitable separator for a specific reservoir enthalpy, mass flow rate and operating pressure. Improper separator sizing can cause higher initial cost or lower separator efficiency (high brine carryover).

The selection of separator design is mostly up to the field operator experience, technology provider and the separator designer. The vertical cyclone separator has become more popular and dominates the trend of design worldwide because of its simple design, lower pressure drop, absence of moving parts, low cost, and high output quality and efficiency (Hoffmann and Stein, 2007). However, the cyclone separator works properly only in a given flow regime (Povarov and Nikolskiy, 2005). Moghaddam (2006) argued that the horizontal separator is more effective because water droplets are at right angle with the steam flow, which leads to the separator maintenance to be easier than the vertical type separator. The early separator designs are installed at each well-head where it requires more separators, valves and longer pipelines at higher initial cost. Currently, the separator design tends be more centralized separation stations to better handle fluid collection and separation for bigger power plants. Hence, larger separators are expected to accommodate large fluid flows. However, design and fabrications limitations can arise for bigger separator, which affects stress distribution between the shells (Pointon et al., 2009). At the same time centralized separation increase the risk of water carry over with the steam to the turbine due to the limited scrubbing pipelines lengths.

Different flow regimes can form in two-phase fluid geothermal pipelines; some of these flow regimes cause vibration. It is necessary to understand the two-phase flow behavior during separator sizing (Zarrouk and Purnanto, 2014). Therefore, robust design is needed to prevent vibration and slugging flow. Separator size is directly correlated to the material needed and the production cost. Higher surface area of the vessel will increase production cost. Some studies show that a horizontal separator is more economical than a vertical separator (Povarov and Nikolskiy, 2005). On the other hand, others think that vertical separators can achieve higher efficiency (Hoffman and Stein, 2007; Lazalde Crabtree, 1984).

Good material management is crucial during power plant construction. Material management involves a combination of the following: buying, storage and materials movement (Arnold, 2001). In order to achieve a speedy and economic project, the proper choice of separator is now recognized as one of the important points in project planning and control. The selection of the optimal size separator can contribute to the cost of a project. Moreover, its selection will affect the required effort and time, as well as the project productivity. Larger separators need more construction material, more storage space, complex delivery and additional handling effort during installation.

This work does not consider the estimation of separator efficiency, but only focus on the separator sizing.

2. SEPARATOR SIZING

2.1 Svrcek and Monnery's method

Svrcek and Monnery (1993) divided the separation stages into three processes: primary separation, secondary separation and mist elimination. In the primary separation, the largest water droplets enter the separator through an inlet diverter and are then separated by gravity forces. The secondary separation is a process where the smaller water droplets are separated in the disengagement area and then move downward by gravity. The last step is mist elimination using coalescing devices, which have a tortuous shape to form bigger droplets from smaller droplets and then drops downward by gravity. The first step is to determine the terminal velocity (*Ut*) using the Sauders-Brown equation as Eq. 1 to calculate the disengagement area.

$$Ut = K'\left(\frac{\rho l-\rho v}{\rho v}\right)^{0.5} \tag{1}$$

Where, (ρl) is the liquid density in kg/m^3; (ρv) is the vapor density in kg/m^3; and *Ut* is the terminal velocity (m/s).

The *K'* value is a function of pressure, where *K'* for most systems with mist eliminators is between 0.055 and 0.131 (m/s), whereas for common systems without mist eliminators, the *K'* should be 0.5. *Uv* is allowable vertical velocity and typically the value is between 0.75*Ut* and *Ut*. The hold-up time and surge time should be considered in the separator sizing. The hold-up time is the required time to reduce the water from normal liquid level (*NLL*) to low liquid level (*LLL*). The hold-up time is important as the safety control during the operation. The surge time is the required time to increase the water level from normal liquid level (*NLL*) to high liquid level (*HLL*). Svrcek and Monnery (1993) suggested that the surge time is half the hold-up time for the first trial if there is not a specific requirement. The general hold up and surge times are given in Table 1.

Table 1 Hold up and surge times (Svrcek and Monnery, 1993)

Services	**Hold Up Times (min)**	**Surge Times (min)**
Unit feed drum	10	5
Separator		
- feed to column	5	3
- feed to other drum or thankage		
a) with pump or through separator	5	2
b) without pump	2	1
- feed to fired heater	10	3

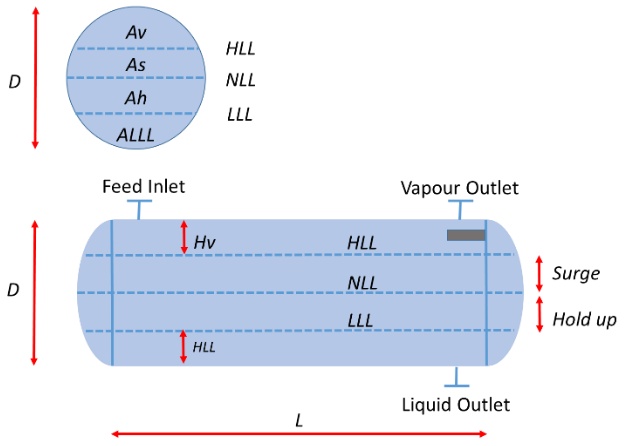

Figure 1. Horizontal Separator (after Svrcek and Moonery, 1993)

Table 2. The general estimation of L/D ratio (after Svrcek and Monnery, 1993)

Operating Pressure (barg)	L/D ratio
0-17.24	3
17.25-34.47	4
34.48 and higher	5

Initially, determine the vapor volumetric flow rate (*Qv*) and liquid volumetric flow rate (*Ql*).

$$Q_v = \frac{\dot{m}v}{\rho v} \tag{2}$$

$$Q_l = \frac{\dot{m}l}{\rho l} \tag{3}$$

Where $\dot{m}v$ is the vapor flow rate (kg/s); ρv is the vapor density (kg/m^3); *Qv* is the vapor volumetric flow rate (m^3/s); and *Ql* is the liquid volumetric flow rate (m^3/s).

By determining the hold-up time and surge time from Table 1 and calculating the liquid volumetric flow rate, Equations 4 and 5 are obtained and can be used to calculate the hold-up volume and surge volume. Then use Equation 6 to set the diameter of the vessel.

$$Vh = Th \ x \ Ql \tag{4}$$

$$Vs = Ts \ x \ Ql \tag{5}$$

$$D = \left(\frac{4(Vh+Vs)}{0.6\pi\left(\frac{L}{D}\right)}\right)^{\frac{1}{3}} \tag{6}$$

Where, *Th* is the hold-up time (s); Ts is the surge time (s); *Ql* is the liquid volumetric flow rate (m^3/s); *Vh* is the hold-up volume (m^3); *Vs* is the surge volume (m^3) and *D* is the vessel diameter (m).

Calculate the total cross sectional area and the low-level liquid height to obtain the low liquid area (*ALLL*) using Eq. (7) and (8):

$$At = 0.25\,\pi\,D^2 \tag{7}$$

$$HLLL = (0.5\,D) + 0.1778 \tag{8}$$

Where, *D* is the vessel diameter (m); *At* is the total cross sectional area (m^2) and *HLLL* is the low liquid level height (m).

Using *HLLL/D*, calculate the *ALLL/At* ratio.
y = H/D and *x =A/At*

$$y = \frac{a + cx + ex^2 + gx^3 + ix^4}{1 + bx + dx^2 + fx^3 + hx^4} \tag{9}$$

a = - 4.75593 x 10^{-3}
b = 3.924091
c = 0.174875
d = - 6.358805
e = 5.668973
f = 4.018448
g = - 4.916411
h = - 1.801705
i = - 0.145348

Set the vapour disengagement area height (*Hv*) 0.069 m and equating it using Eq. (9) to get the vapour disengagement area height. Then the vessel length can be calculated

$$L = \frac{Vh + Vs}{At + Av + ALLL} \tag{10}$$

Where, Vh is the holdup volume (m^3); Vs is the surge volume (m^3); At is the total cross sectional area (m^2); Av is the vapour disengagement area required (m^2) and $ALLL$ is the cross section area for LLL (m^2).

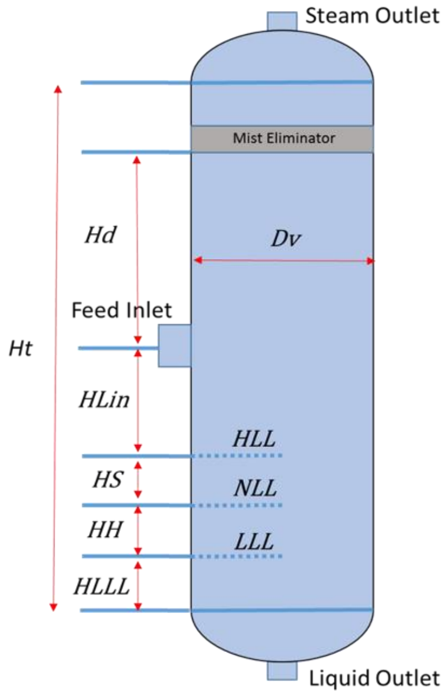

Figure 2. Top Outlet Cyclone Separator (after Svrcek and Moonery, 1993)

Similar to the horizontal separator calculation, to determine the vapour volumetric flow rate (*Qv*), the liquid volumetric flow rate (*Ql*), the hold-up volume (*Vh*), the surge volume (*Vs*), the low liquid level height (*HLLL*) using Equations (2), (3), (4), (5) and (8) respectively. Then use Equation (11) to obtain the vapour disengagement diameter (*Dvd*). Equation (12) is used to calculate the distance between normal liquid level (*NLL*) and low liquid level (*LLL*) as well as Equation (13) to determine the distance between normal liquid level (*NLL*) and high liquid level (*HLL*).

$$Dvd = \left(\frac{4(Qv)}{\pi Uv}\right)^{0.5} \tag{11}$$

$$HH = \frac{Vh}{\left(\frac{\pi}{4}\right) Dvd^2} \tag{12}$$

$$HS = \frac{Vs}{\left(\frac{\pi}{4}\right) Dvd^2} \tag{13}$$

Where, *Dvd* is the vapour disengagement diameter (m); *Qv* is the vapour volumetric flow rate (m^3/s); *Uv* is the allowable vapour velocity (m/s); *HH* is the holdup height (*m*); *Vh* is the hold-up volume (m^3); *HS* is the surge height (m) and *Vs* is the surge volume (m^3).

Determine the *HLin* and *Hd* so that the total height of the vessel can be obtained.

$$\lambda = \frac{Ql}{Ql + Qv} \tag{14}$$

$$Qm = Ql + Qv \tag{15}$$

$$\rho m = \rho l\, \lambda + \rho v\, (1 - \lambda) \tag{16}$$

$$dn = \left(\frac{\frac{4Qm}{\pi 60}}{\sqrt{\rho m}}\right)^{0.5} \tag{17}$$

$$HLin = 0.3048 + dn\ (with\ inlet\ diverter) \tag{18}$$

$$HLin = 0.3048 + 0.5dn\ (without\ inlet\ diverter) \tag{19}$$

$$Hd = 10.9728 + 0.5dn\ (without\ mist\ eliminator) \tag{20}$$

$$Hd = 7.3152 + 0.5dn\ (with\ mist\ eliminator) \tag{21}$$

$$Ht = HLLL + HH + HLin + Hd + HMe \tag{23}$$

Where, *Ql* is the liquid volumetric flow rate (m3/s); *Qv* is the vapour volumetric flow rate (m3/s); *Qm* is the the mixture volumetric flow rate (m3/s); *ρm* is the mixture density (kg/m3); *ρl* is the liquid density (kg/m3); *ρv* is the vapour density (kg/m3); *dn* is the nozzle diameter (m); *HLin* is the distance between *HLL* to inlet nozzle centerline height (m); *HLLL* is the low liquid level height (m); *HH* is the hold-up height (m); Hs is the surge height (m); *Hd* is the disengagement height (m); *HMe* is the distance between mist eliminator to top tank height (m) and *Ht* is the total separator height (m).

2.2. Gerunda's Method

Similar to the Svrcek and Monnery (1993) method, the terminal vapour velocity should be calculated where the Souders and Brown equation is used as given in Equation (1). Gerunda (1981) recommended 0.069 (m/s) for the *K'* value and 0.15 *Ut* as the allowable vapour velocity for a conservative design. Then, the horizontal separators design criteria are as follows:

a. The minimum liquid level is not below the centre-line of the vessel, while the maximum liquid level does not rise above 0.3 m from the top.
b. The volume of dished head is negligible during the separator sizing
c. Inlet and outlet nozzle should be closer each other to the vessel tangent lines
d. The anti-vortex baffles should be installed in the liquid outlets

By determining the vapour volumetric flow rate (*Qv*) and the liquid volumetric flow rate (*Ql*) using Equations (2) and (3) respectively, Equation (24) is obtained to calculate the horizontal vessel diameter based on liquid separation, while Equation (25) is used to calculate the horizontal vessel diameter based on holding time approach. Thus, the length of the horizontal vessel can be obtained Using (L/D) ratio depends on the separator pressure from Table 1.

$$D = \left(\frac{Qv}{\left(\frac{L}{D}\right) \cdot \left(\frac{\pi}{4}\right) Uv\ Ut}\right)^{\left(\frac{1}{2}\right)} \tag{24}$$

$$D = (\frac{Th.Ql}{3\left(\frac{\pi}{4}\right)Fa})^{(\frac{1}{3})} \quad (25)$$

Where, *Qv* is the vapour volumetric flow rate (m^3/s); *Ql* is the liquid volumetric flow rate (m^3/s); *Uv* is the allowable vapour velocity (m/s); *Ut* is the terminal vapour velocity (m/s); *Fa* is the liquid space area (for the first trial uses *Fa* = *Fh* = 0.5); and *D* is the vessel diameter (m).

For vertical separator, the first step is to determine the cross-sectional area of the separator (*Ad*). Therefore, the vessel diameter can be calculated using Eq. (27).

$$Ad = \frac{Qv}{Uv} \quad (26)$$

$$D = (\frac{4Ad}{\pi})^{0.5} \quad (27)$$

Where, Uv is the allowable vapour (m/s); Qv is the vapour volumetric flow rate (m^3/s); *Ad* is the cross-sectional area of the separator (m^2); and *D* is the vessel diameter (m).

To get the approximation of vessel height , liquid level (*HH*), height of the disengagement space (*Hd*), distance between the inlet nozzle and the maximum liquid level (*HLin*), and distance between the top tangent line and the elimination pad (*Hs*) should be considered.

$$HH = 300\frac{Ql}{Ad} \quad (28)$$

$$Hd = D \quad (29)$$

$$HLin = 0.5\ D \quad (30)$$

$$Hs = D \quad (31)$$

$$Ht = HH + Hd + HLin + Hs \quad (32)$$

Where, *Ad* is the cross-sectional area of the separator (m^2); *HH* is the hold-up height (m); *D* is the vessel diameter (m); *Hd* is the disengagement height (m); *HLin* is the distance between *HLL* to inlet nozzle centerline height (m); *Hs* is the surge height (m) and *Ht* is the total separator height (m)

2.3. Bangma's Method

Despite the utilization of the vertical top outlet cyclone separator (TOC) also known as the wood separator, the bottom outlet cyclone separator (BOC) also known as the weber separator became more popular (Zarrouk and Purnanto 2015). For the (BOC), the separated steam line is located at the bottom of the vessel, making it simpler to support the steam line near the ground (Bangma, 1961). The basic principal of the (BOC) is similar with the (TOC). In the cyclone separator, a centrifugal force is created so that the liquid goes to the separator wall and the vapour remains in the middle of separator. Then, the liquid moves downward to the bottom of separator by gravity, while the vapour will enter the tube in the middle and leave the separator from the bottom pipeline.

During BOC separator sizing, the inlet pipe diameter should be calculated. To solve this problem, the following steps can be used: determine the vapour volumetric flow rate (*Qv*) as given by Equation (2), determine the liquid volumetric flow rate (*Ql*) as given by Equation (3), calculate the cross sectional area of inlet nozzle (*A*) as given by Equation (33). Thus, Equation (34) is obtained to get the inlet pipe diameter. Bangma (1961), recommended that the vessel diameter and total height are the function of the inlet pipe diameter as given by Equations (35) and (36) respectively.

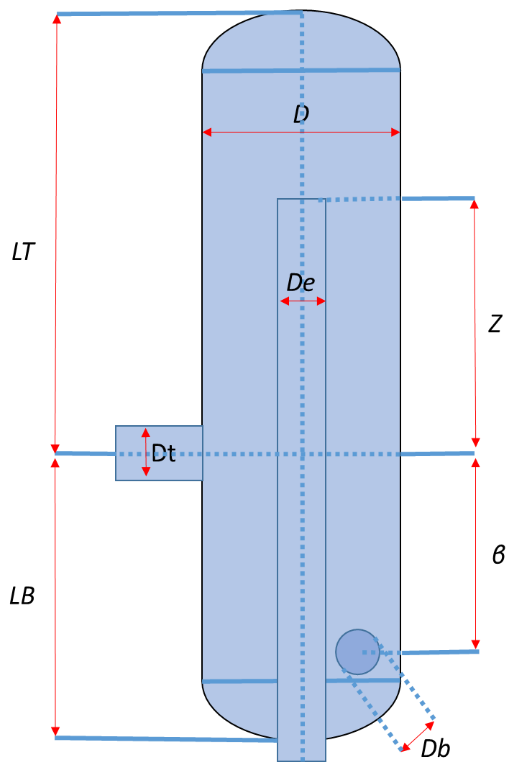

Figure 3. Bottom Outlet Cyclone Separator (after Bangma, 1961)

$$A = \frac{Qv}{Ut} \quad (33)$$

$$Dt = (\frac{4A}{\pi})^{\frac{1}{2}} \quad (34)$$

$$D = 3\ Dt \quad (35)$$

$$TL = 11.5\ Dt \quad (36)$$

Where, Qv is the vapour volumetric flow rate (m^3/s); *Ut* is the terminal vapour velocity (m/s); and *A* is the cross sectional area of inlet nozzle (m^2); *Dt* is the inlet pipe diameter (m); and *TL* is the total height (m).

3. RESULT

Several input parameters are needed during the separator sizing: reservoir enthalpy, mass flow rate and separator pressure. In this section, three different attempts (tests) are made to investigate the separator size: vessel diameter, vessel length, surface area and vessel volume using the correlations given in section 2. The first test uses different sets of separator pressures with constant flow rate and enthalpy. The second test is used to find the effect of flow rate changes on the separator size at a constant separator pressure and enthalpy. The last test observes the separator size based on different produced enthalpies.

A. First test

Parameters :

- Reservoir enthalpy = 1200 kJ/kg
- Total mass flow rate = 500 t/h

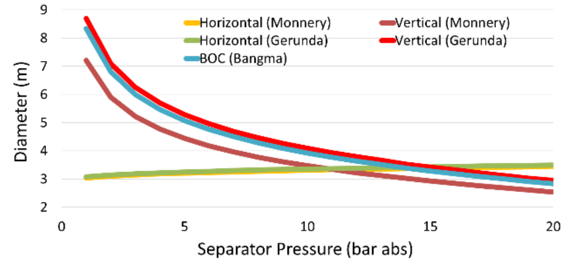

Figure 5. Vessel diameter for different separsator pressure

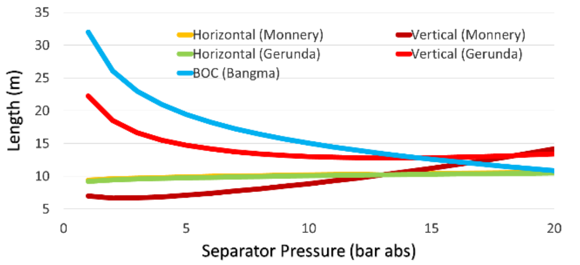

Figure 6. Vessel length for different separsator pressure

Figure 5 above shows the different vessel diameters vs separator pressure using five different methods. It can be seen that the horizontal separator has not a significant change in vessel diameter which ranges between 3 and 4 m. On the other hand, the vertical separator has a high vessel diameter when operating at low separation pressure. Vertical separators are mainly dominated by the centrifugal forces where dependant on the inlet velocity and vessel diameter. Lower separation pressure results in higher dryness factor and inlet velocity. On the other hand, the horizontal separator needs larger size to accommodate holdup and surge in order to give the liquid particles enough time to settle out before the steam leaves the separator at higher fluid velocity. The diameter of horizontal separator will be larger than the vertical separator when it is operated at high separator pressure.

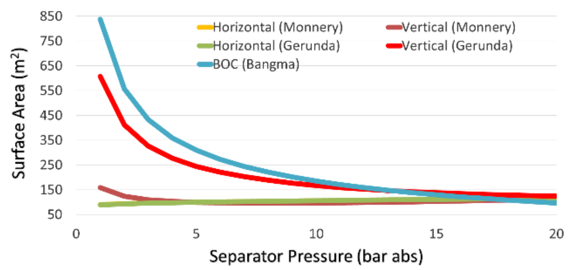

Figure 7. Vessel surface area at different pressure

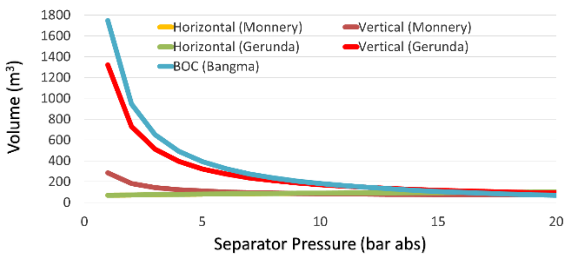

Figure 8. Vessel volume at different pressure

The horizontal separator needs smaller outside surface area (Figure 7) as well as the vessel volume (Figure 8) for lower separation pressure compared with veritical separators.

B. Second test

Parameters :

- Reservoir enthalpy = 1200 kJ/kg
- Separator pressure = 15 bar abs

The separator diameter (Figure 9) and length (Figure 10) Increase with the increase of mass flow rate Lower mass flow rate will need lower separator diameter and length, while larger separator diameter and length are needed for higher mass flow rate. Figures 9 and 10 also show that Horizontal separator is larger in diameter and shorter in length than Vertical separators for the same load.

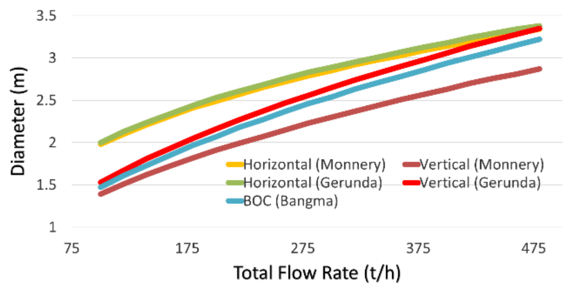

Figure 9. Vessel diameter at different flow rate

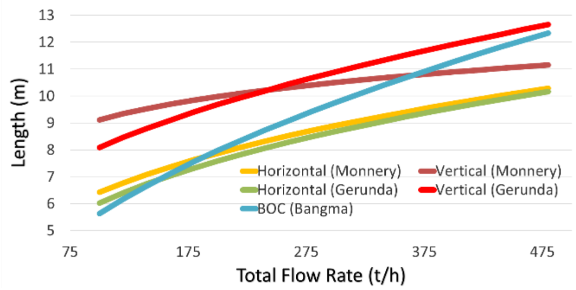

Figure 10. Vessel length at different flow rate

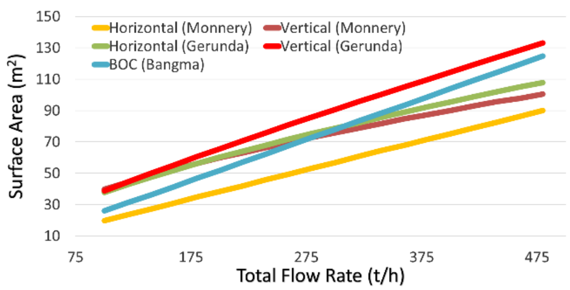

Figure 11. Vessel surface area at different flow rate

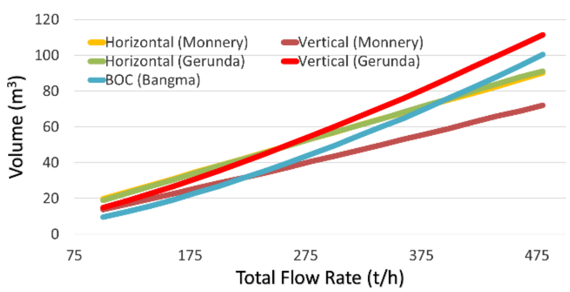

Figure 12. Vessel volume at different flow rate.

There is no significant difference in the surface area and volume. A lower flow rate needs smaller surface area and volume. The separator size will increase when the flow rate increases.

C. Third test

Parameters :

- Separator Pressure = 15 bar abs
- Total mass flow rate = 500 t/h

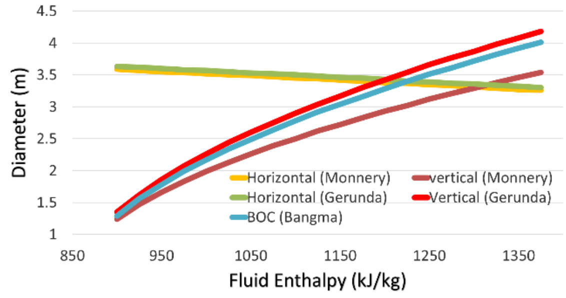

Figure 13. Vessel diameter at different fluid enthalpy

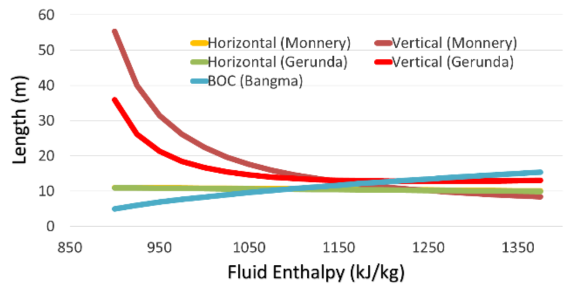

Figure 14. Vessel length at different fluid enthalpy

Figure 13 shows the diameter of vertical separators increasing rapidly, while the horizontal separators decrease slightly. Moreover, the length of the vertical separators decreased significantly in the beginning and remains stable at high enthalpy as shown in Figure 14.

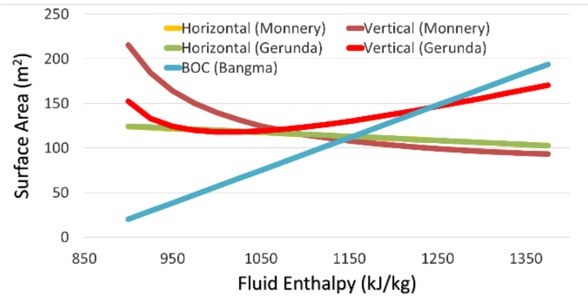

Figure 15. Vessel surface area at different fluid enthalpy

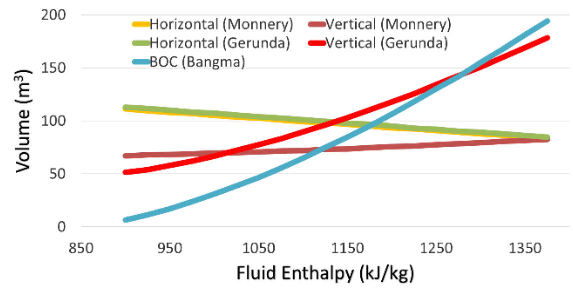

Figure 16. Vessel volume at different fluid enthalpy

Figures 15 and 16 show the horizontal separator has a slight decrease of surface area and volume. Yet the volume of separator increases dramatically for Gerunda's and Bangma's method, while Monnery's method has a slight increase. Therefore, Horizontal separators have a larger vessil surface area and volume when operating at high enthalpy whereas vertical separators are resultes in smaller vessil surface area when operating at low enthalpy as it result in lower volumetric flow rate.

4. CONCLUSION

The input parameters for separator design consist of reservoir enthalpy, mass flow rate and pressure. Different input parameters cause a different optimum separator design. The size of separators can vary based on the fluid enthalpy, separation pressure and flow rate. Horizontal separators seem to be smaller than vertical separators when it operates at low separation pressure and higher enthalpy. However, the fluid flow rate significantly affects the separator size. The vessel size has a linear correlation to mass flow rate where higher mass flow rate needs a bigger vessel. It is crucial to get accurate data of the input parameters. Inaccurate reservoir data may lead to incorrect separator selection (type and size). As to material management, choosing smaller separator for minimizing production cost since its vessel uses less material. The same with the delivery, a smaller vessel is relatively easier for transporting from manufacturer to project site. The separator sizing is not the only factor. Obviously, some parameters should be considered when selecting the separator pressure, such as the silica saturation index (SSI), pressure drop and separator efficiency.

REFERENCES

Arnold, J., 2001. Introduction to Materials Management, 6th edition Prentice-Hall, Englewood Cliffs, New Jersey. pp. 241-253.

Damodara, K., 2008. Materials Management: They Key to Succesful Project Management, Journal of Management in Engineering, ASCE, 15(1), 30-34.

DiPippo, R., 2012. Geothermal Power Plants Principles, Applications, Case Studies and Environmental Impact, third ed. Elsevier Ltd., United States of America.

Faulkner., W.B. & Shaw., B.W., 2006. Efficiency and Pressure Drop of Cyclones Across a Range of Inlet Velocities, Vol. 22(1), p 155-161.

Foong, K.C., 2005. Design Concept for a More Efficient Steam-Water Separator. In: Proceedings of the World Geothermal Congress, Antalya, Turkey.

Gerunda, A., 1981. How to Size Liquid Vapor Separators, Chemical Engineering, p 81-84.

Hoffmann, A.C. & Stein, L.E., 2007. Gas Cyclone and Swirl Tubes; Principles, Design and Operation, second ed. Springer, New York.

Lazalde-Crabtree, H., 1984. Design Approach of Steam-Water Separators and Steam Dryers for Geothermal Applications. Geotherm. Resour. Counc. Bull., 11-20.

Moghaddam, A.R., 2006. A Conceptual Design of a Geothermal Combined Cycle and Comparison with a Single Flash Power Plant for Well NWS-4, Sabalan, Iran. The United Nations University, Iceland.

Mulyandasari, V., 2011. Separator Selection and Sizing, Engineering Design Guideline, p 8-16.

Pointon, A.R., Mills, T.D., Seil, G.J., Zhang, Q., 2009. Computational Fluid Dynamic Techniques for Validating Geothermal Separator Sizing. GRC Trans. 33, 943-948.

Povarov, O. & Nikolskiy, A.I., 2005. Experience of Creation and Operation of Geothermal Energy Power Plants in Cold Climate Conditions. In: Proceedings of The World Geothermal Congress, Antalya, Turkey.

Purnanto, M.H., Zarrouk, S.J., & Cater, J.E., 2012. CFD Modelling of Two-Phase Flow Inside Geothermal Steam-Water Separator. In: Proceedings of the 34th NZ Geothermal Workshop, Auckland, New Zealand.

Souders, M. & Brown. G.G., 1934. Design of Fractionating Columns-Entrainment and Capacity, Industrial and Engineering Chemistry, Volume 26, Issue 1, p 98-103.

Svrcek, W.Y. & Monnery, W.D., 1993. Design Two-Phase Separators Within the Right Limits: Fluids/Solids Handling, 53-60.

Zarrouk, S.J. & Moon, H., 2014. Efficiency of Geothermal Power Plants: a worldwide review. Geothermics 51, 142-153.

Zarrouk, S.J. & Purnanto, M.H., 2015. Geothermal steam-water separator: A design Overview. Geothermics, 53, 236-254.

Nomenclature

A	cross sectional area of inlet nozzle (m^2)
$ALLL$	cross section area for LLL (m^2)
Ad	cross-sectional area of the separator (m^2)
At	total cross-sectional area (m^2)
Av	vapour disengagement area required (m^2)
BOC	bottom outlet cyclone separator
D	vessel diameter (m)
Dt	inlet pipe diameter (m)
dn	nozzle diameter (m)
Dvd	vessel diameter (m)
Fa	fraction of area
Fh	fraction of height
Hd	disengagement height (m)
HH	hold up height (m)
$HLin$	HLL to inlet nozzle centerline height (m)
HLL	high liquid level (m)
$HLLL$	low liquid level height (m)
HMe	mist eliminator to top tank height (m)
Hs	surge height (m)
Ht	total separator height (m)
K'	a function of pressure
LLL	low liquid level (m)
$\dot{m}v$	vapour flow rate (kg/s)
NLL	normal liquid level
Ql	liquid volumetric flow rate (m^3/s)
Qv	vapour volumetric flow rate (m^3/s)
Qm	mixture volumetric flow rate (m^3/s)
Th	hold up time (s)
TOC	top outlet cyclone separator
TL	total height (m)
Ts	surge time (s)
Ut	terminal vapour velocity (m/s)
Uv	allowable vapour velocity (m/s)
Vh	hold up volume (m^3)
Vs	surge volume (m^3)
ρl	liquid density in (kg/m^3)
ρm	mixture density (kg/m^3)
ρv	vapour density (kg/m^3)