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Reykjanes Geothermal Field: Development of Combined Vertical and Horizontal Separator

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ABSTRACT

In the Reykjanes geothermal power plant, the steam is separated from brine at high pressure and the hot brine disposed of. Bottoming unit is being developed in which the hot brine will be flashed in two stages and the medium- and low-pressure steam used in a dual flash turbine to generate 30 MW of electricity. Two horizontal separators are used in the power plant for separation of high-pressure steam and brine, but although very effective, horizontal separators are not suitable for the low-pressure separators because of high silica scaling rate. Effective steam purification is very important already in the first step of separation because of the high salinity and silica content of the brine. For obtaining the dual purpose of effective steam separation and minimal scaling, a combined vertical and horizontal separator was developed. In the newly developed separator, the brine tangentially enters the vertical part and is separated from the steam by centrifugal action. The steam then flows into the horizontal part and droplets are separated by gravitational settling and finally the steam is purified in a mist eliminator. The design was tested in an experimental separator for 25 kg/s of 207°C brine, which was flashed in two stages producing 2.5 kg/s of MP-steam at 155°C and 2.0 kg/s of LP-steam at 108°C. The tests were successful and separator efficiency of 99.99% could be obtained. The design is now being scaled up for a full-size separation of 410 kg/s of brine and production of 38 kg/s of MP-steam and 34 kg/s of LP- steam.

1. INTRODUCTION

HS-orka operates a 100 MW power plant in the Reykjanes geothermal field in Iceland. The plant is fed with steam from 1130 to 2700 m deep wells which tap 250 to 320°C hot brine of seawater salinity from the geothermal reservoir. In the power plant, 2 x 85 kg/s of steam is separated from the brine at 18 bar separator pressure. The steam is used for powering two 50 MW turbines and the exhaust steam is condensed at 40-45°C in surface condensers. The non-condensable gas is extracted from the condenser and discharged through a chimney. The separated 207°C hot brine is now partly reinjected and partly disposed of into the ocean. The energy content of the disposed brine is considerable and can be used to generate at least 30 MW of electricity.

Because of the high silica concentration and high salinity severe scaling will occur when the brine is flashed to lower temperature in a separator. The use of acid for scale mitigation, although effective, is considered unattractive and therefore a new separator technology was developed to control the silica scaling with critical nozzles and without the use of chemicals. This new technology is described in a separate paper at this convention (Lund et al., 2020).

Two horizontal separators are used in the power plant for separation of high-pressure steam and brine, but although very effective, horizontal separators are not suitable for the low-pressure separators because of high silica scaling rate in unmodified brine. Effective steam purification is very important already in the first step of separation because of the high salinity and silica content of the brine. For obtaining the dual purpose of effective steam separation and minimal scaling, a combined vertical and horizontal separator was developed. An experimental separator unit was designed for 25 kg/s of 207°C brine, which was flashed in two stages at 155°C and 108°C and its testing and development is described in this paper.

2. GEOTHERMAL STEAM SEPARATORS

Vertical cyclone separators are commonly used for separating steam from brine in geothermal operation. Since the installation of first separators in New Zealand in the 1950s, various separator designs have been utilized. Generally, power plants influenced by New Zealand technology use vertical separators but since the 1990s horizontal gravity separators have been used in Icelandic power plants and also e.g. in Russia, Japan and US (Zarrouka and Purnanto, 2015). First installations in Iceland used vertical separators (Bjarnarflag: 1968, Krafla unit 1: 1977 and Svartsengi unit 1 and 3: 1978 and 1981). In newer installation horizontal separators have exclusively been used (Svartsengi units 5 and 6: 1997 and 2007, Nesjavellir units 1 to 4: 1998, 2001 and 2005, Krafla unit 2: 1999, Hellisheiði units 1 to 7: 2006, 2007, 2008 and 2011 and Reykjanes unit 1 and 2: 2006). Experience from the operation of horizontal separators in Icelandic geothermal power plants, which spans decades of operation, is good. Very good results have been obtained in terms of reductions of carryover using horizontal separators (Ingimundarson et al., 2017).

Both vertical and horizontal designs can obtain separator efficiency of 99.9%. The efficiency of the cyclone separator is highly dependent on inflow velocity and it achieves the highest efficiency when the steam inlet velocity is between 30 and 40 m/s, but at higher velocity the efficiency deteriorates rapidly. Recommended upward steam velocity inside the cyclone is in the range of 2.5 to 4.0 m/s and with optimal design the separator efficiency can reach 99.97%, (Lazalde-Crabtree, 1984 and Foong, 2005). The horizontal separator has some advantages. By optimal design the horizontal separator volume is smaller, and the material weight can be as low as 54% of the weight of cyclone separator with similar efficiency (Vieira, 2015). The inlet flow velocity in horizontal separators does not influence the efficiency if an inflow distributor is used, and mist eliminators installed in the horizontal separator outlet will improve the efficiency (Rizaldy et al., 2016).

In recent power plants in Iceland the steam separation is done in a centralized station located several hundred meters from the power plant. By this arrangement the steam pipe to the power station acts as a scrubber and removes entrained carryover in the steam and a steam purity of more than 99.99% can be obtained. In Reykjanes power plant, the high salinity brine with chloride concentration of 22,000 ppm calls for a separation efficiency of better than 99.995% to lower the chloride content below the turbine manufacturer's absolute maximum level of 1 ppm, and even to 99.9995% to lower it below the recommended level of 0.1 ppm. This can be obtained in the Reykjanes plant by a steam transfer pipe of 1.25 km between the separator station and the power plant with an overall separating efficiency better than 99.9995%, and chloride content in the steam below 0.1 ppm when the steam enters the turbines (Óskarsson, 2018).

The new Reykjanes bottoming plant will be located only 50 meters from the separator station and steam purity will therefore not be significantly improved by the scrubbing action of the steam pipe. Because of this, very good efficiency must be obtained already in the separators of the bottoming plant. Cyclone separators with inlet nozzles with critical flow will be used to mitigate scaling in the separators. At critical flow the inlet velocity will be much higher than the optimal inlet velocity of 30-40 m/s for cyclone separators which will increase mist formation in the separator. It was therefore decided to try to combine the vertical cyclone separator with a horizontal separator in order to obtain the required separation efficiency and also to install a vane mist eliminator in the separator.

3. EXPERIMENTAL SEPARATOR UNIT

An experimental two-stage separator unit was built close to the high-pressure separators of the power plant and connected to the discharge pipes. It was capable of separating 25 kg/s of 207°C brine and produce 2.8 kg/s of MP-steam at 155°C and 2.0 kg/s of LP-steam at 108°C. Each separator was combined with horizontal droplet settler with vane mist eliminator to improve the separator efficiency. The flow pattern inside the separators could be studied through sight glasses. The separators are shown in Figures 1 and 2.

The inflow was controlled by a fixed diameter nozzle with critical flow. The steam outlet valve controlled the pressure in the MP-separator automatically. A fixed diameter nozzle with critical flow also controlled the flow of brine from MP-separator to the LP-separator. A guided radar level sensor in an external pipe monitored the level in the MP-separator. The pressure in the LP-separator unit was manually adjusted so that the level of brine in the barometric outlet pipe in the basin was 4 meters below the level in the basin.

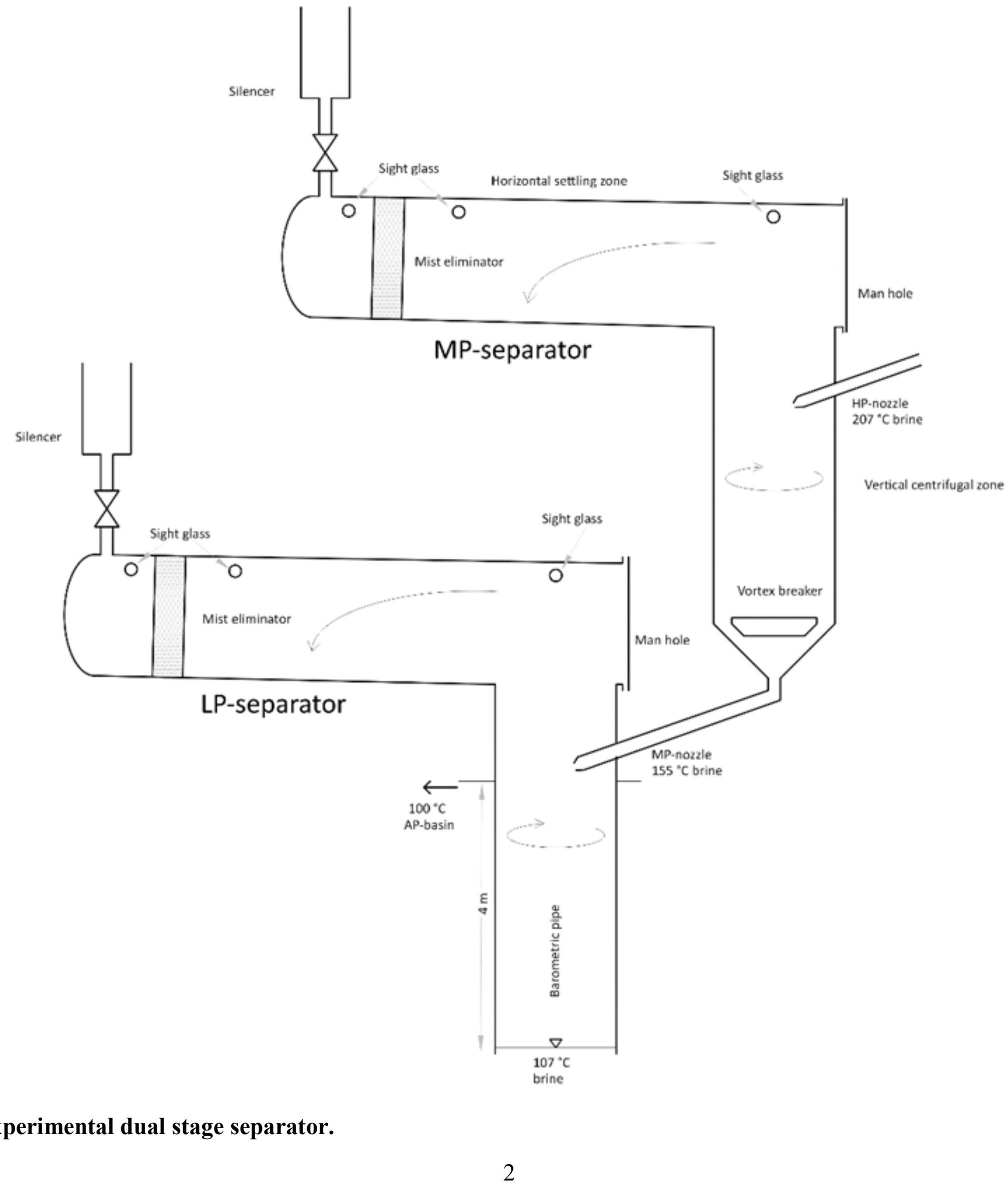

Figure 1: Experimental dual stage separator.

Figure 2: Experimental separators.

Several types of nozzles and different nozzle alignments were tested for optimal separation efficiency. Best efficiency was obtained when the nozzles were exactly tangent to the separator walls and inclined 30° downward (Figure 3).

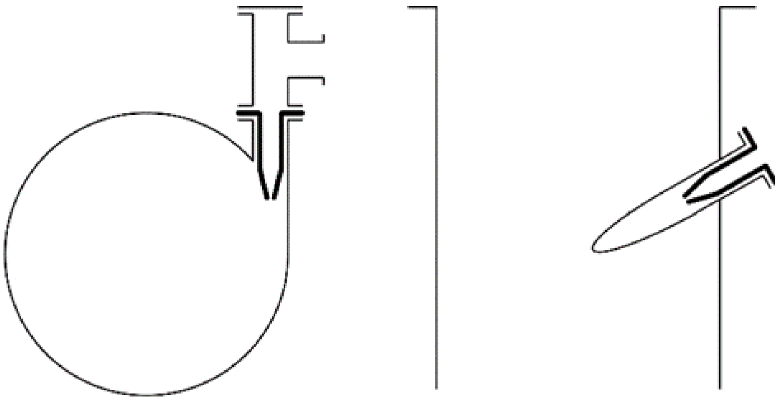

Figure 3 Tangential nozzle with 30° inclination.

4. SEPARATOR EFFICIENCY

For measuring the separator efficiency sample taps were installed (Figure 4). Tap one collected the brine flowing back from the horizontal section to the vertical section. By measuring the flow and analyzing the mineral content the entrained carryover of brine in the steam could be calculated. The second tap collected the brine trapped in the mist separator which allowed for calculation of its efficiency. Finally, narrow steam pipes were installed on the steam outlet with high steam velocity and mist flow in the pipe. By using an iso-kinetic nozzle, representative samples for measurement of final entrained carryover in the steam from the unit could be collected. The separator efficiency of each section could thus by calculated. At a steam velocity of 1.94 to 2.24 m/s the separating efficiency of the vertical section was on average 97.7% and slightly worse at higher steam velocity. The horizontal section separated on average 68% of the brine droplets entering it. More brine was separated from the steam in the horizontal section when the efficiency of the vertical section was worse. The horizontal section improved the overall separating efficiency to 99.5% on average. The mist eliminator removed 97% of the mist entering it and was able to improve the separating efficiency to better than 99.99%. This is however not sufficient to pass the turbine manufacturers criteria and final steam purity will therefore have to rely on the scrubbing action of the steam transfer pipe and the wire mesh mist eliminators in front of the turbine.

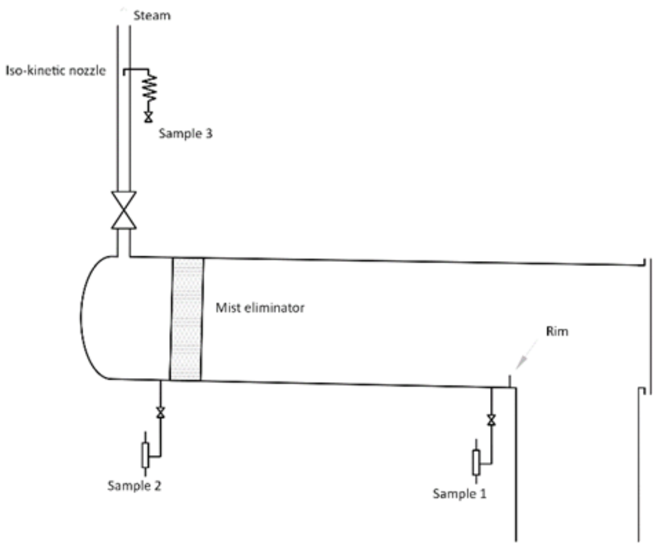

Figure 4 Measurement of carryover. Location of sampling taps.

5. FULL-SIZE SCALE UP

One of the results from the experiments was that if the superficial velocity of steam up through the separator exceeded 2.0 m/s, the separation efficiency of the vertical part decreased, resulting in increased water load in the horizontal part. This limit is somewhat lower than recommended for conventional vertical geothermal steam separators (Lazalde-Crabtree, 1984). The critical flow in the inlet nozzle, with the flashing of brine occurring just downstream of it, enhances the atomization of the fluid and larger portion of the brine turns into droplets. This flow regime is different from conventional separators where the flashing occurs mostly upstream of the separator and the inlet velocity is lower. This restriction imposes a lower limit on the diameter of the separator. The jet from the inlet nozzle expands fast because of the flashing with the jet spread angle increasing with more violent phase changes (Polanco et al., 2010). The use of a larger diameter nozzle results in a larger spread area of the jet with larger portion hitting the separator wall with high impact angle. This reduces the swirling effect in the separator since higher portion of the flow does not enter tangentially. In the experimental separator, dividing the inflow on six smaller inlet nozzles was tested. This resulted in less spreading areas of the inlet jets and the jets entered more tangentially. The centrifugal force was increased and the steam core in the center of the separator was elongated. This setup was chosen for the full-size separator with the inflow divided on six inlet nozzles installed all at the same height around the perimeter of the separator. The inclination angle of the nozzles was kept the same as on the experimental separator.

The objective of the horizontal separator is to let droplets fall to the separator bottom due to gravity. The effect of gravity is enhanced in the horizontal section since the drag force and the gravitational force are perpendicular. Optimally, the separator would need to be of infinite length to allow most droplets to settle at the bottom of the separator. Due to impracticality this is not possible, and a cost-effective length needs to be found. This length needs to be enough to keep maintenance on the vane-type demister within scheduled maintenance stops. If the mass load on the vane-type demister is too high, scaling on its vanes will be too excessive and affect the operation of the power plant. Problems such as maintaining separator pressure and a decrease in separation efficiency would occur. A numerical study was conducted of the horizontal part of the separator, the computational domain can be seen in Figure 5.

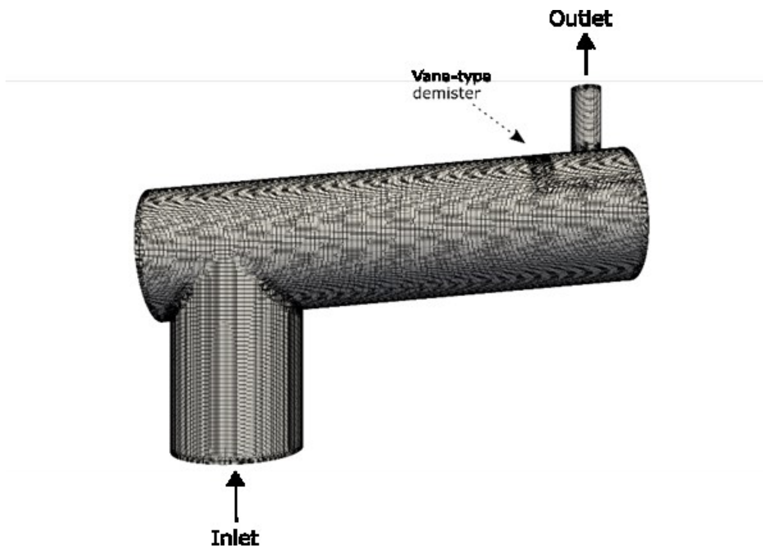

Figure 5: The computational domain of the numerical model used to study droplet trajectories.

The model simulated the flow of steam up through the vertical separator exiting through the outlet pipe. Particles were injected into the steam flow with drag force, gravity force and turbulent dispersion affecting their trajectories. The Stokes number (*St*) of the droplets expresses their ability to follow the streamlines of the steam flow. Droplet size distributions in flashing jets are influenced by various parameters such as thermodynamical conditions, nozzle length and diameter and fluid velocity (Polanco et al., 2010). In this experimental study no work was done to determine droplet size distributions. Therefore, in the numerical model the droplet size distribution was a uniform distribution with droplet diameters from 5 µm to 1000 µm. The model was then used to test different separator lengths and help the designers to determine the necessary length. The model showed that droplets with diameters less than 100 µm ($St < 0.1$) followed the steam path through the separator while droplets with diameters ranging from 100 µm to 300 µm ($St \sim 1$) had more potential to fall to the bottom of the separator. Larger droplets did not escape the vertical part or settled very fast in the horizontal part.

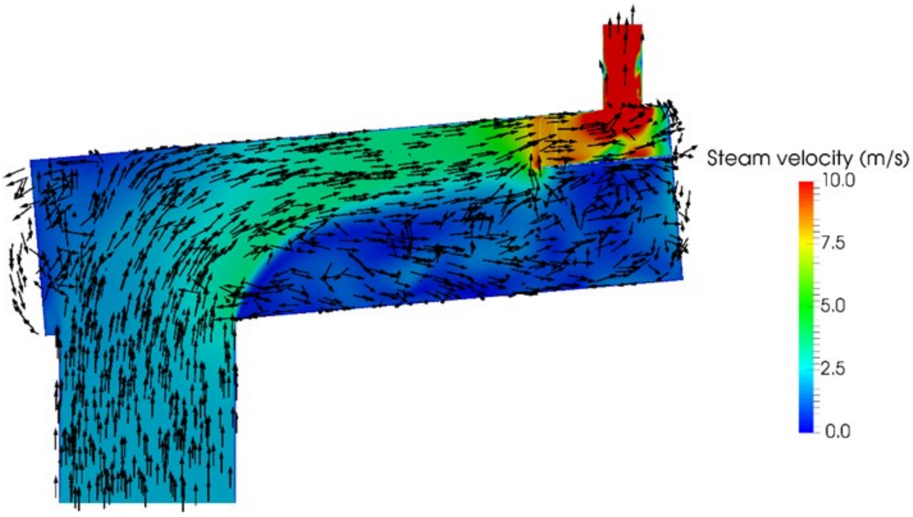

Figure 6: Cross-sectional plane showing steam flow velocity and direction in 3D within the horizontal part.

The scale-up to a full-size separator from the experimental one was based on these considerations among others. The dimensions of the full-scale separator are shown in Table 1, both for the MP Separator and the LP separator. The vertical part height is defined from water level up to highest point on the vertical part. The nozzle inlet height is defined from water level up to the nozzle centerline. The horizontal part length is defined from the highest point of the vertical part to the vane-type demister, measured horizontally.

Table 1: Full-scale separator dimensions.

	MP Separator	LP Separator
Operating Pressure	5.5 bara	1.3 bara
Steam Mass Flow	21.7 kg/s	19.3 kg/s
Diameter	2.25 m	4.1 m
Vertical Part – Height	7.5 m	10.8 m
Vertical Part – Nozzle Inlet Height	3.75 m	5.3 m
Horizontal Part – Length	6.2 m	7.6 m

6. CONCLUSIONS

The experiments confirmed that a separation efficiency of 99,99% can be obtained by combining a vertical and horizontal separator with a mist eliminator in one unit. Based on this result a full-size separator is being designed.

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