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Design Concept for a More Efficient Steam-Water Separator

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ABSTRACT

The Webre steam-water separator design is widely used in New Zealand, Philippines, Indonesia, Kenya and elsewhere in the world. It has been very successful with a separation efficiency claimed to be as high as 99.97%. While this seems adequate, 0.03 % brine carry over equates to about 0.24 TPH for a 100MW plant. The paper looks at designs and the operation of new and old separators and proposes a new equation to calculate separator efficiency. It then presents a conceptual design to improve the separation efficiency by trapping creep water. The design also reduces the pressure drop across the separator and improves access for internal vessel inspection.

1. INTRODUCTION

The current Webre type separator design dates back to the 1950's. It was first used in New Zealand at the Wairakei Geothermal Power Station. Since then, it has been used in many parts of the world to separate steam from brine (geothermal water) in geothermal power projects. Except for improvements in inlet design and internal construction, its design has changed very little.

2. SEPARATOR DEVELOPMENT

Water and steam can be separated by flowing the mixture into a large drum. The lighter steam will rise up while the heavier water will fall to the bottom of the drum. Indeed such a knock out drum (Figure1) is still in use today and it is still being built for new geothermal projects.

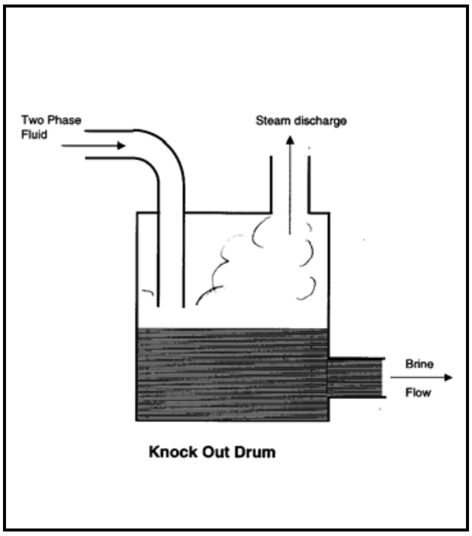

Figure 1 – Knock Out Drum

Faced with the problem of separating brine from steam more efficiently, the early designers would have thought of using the centrifugal effects of fluid going around a curve surface to separate two fluids of different densities (brine and steam) and then use gravity to drop out the heavier brine from the steam. This led to the design of the U bend separator (Figure 2) in 1951, where the two phase fluid (mixture of brine and steam) is made to go around a U bend in a vertical loop to concentrate the brine on the outside wall. As the two separated fluids come down from the loop, gravity accelerates the brine downwards. The lighter phase steam is then extracted from the inside wall.

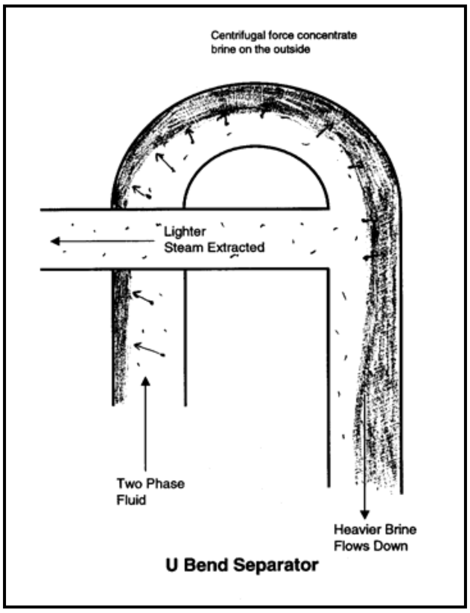

Figure 2 – U Bend Separator

The separation efficiency of the U bend was reported to be only about 80%. A centrifugal separator was later added downstream to improve separation efficiency. Further experimentation showed that the centrifugal separator could handle wet fluid without the U bend and the latter was discarded.

One of the first centrifugal separators used at Wairakei has steam discharge from the top of a vertical vessel and brine discharge from the bottom of the vessel (Figure 3).

The diagram in Bangma's paper showed internal baffles at the top, middle and bottom of the separator. It is speculated that the middle baffle forces the incoming fluid against the wall and spin it at high velocity to separate steam from brine. The top baffle is probably used to prolong the spinning action and to prevent up flowing steam from moving to the centre of the separator early. The bottom baffle is probably an anti vortex plate for the brine.

Later, the separator design was changed to a Webre type with the steam pipe running inside the vessel and coming out at the bottom. This concept is still the most widely used separation method employed in New Zealand geothermal projects and many parts of the world.

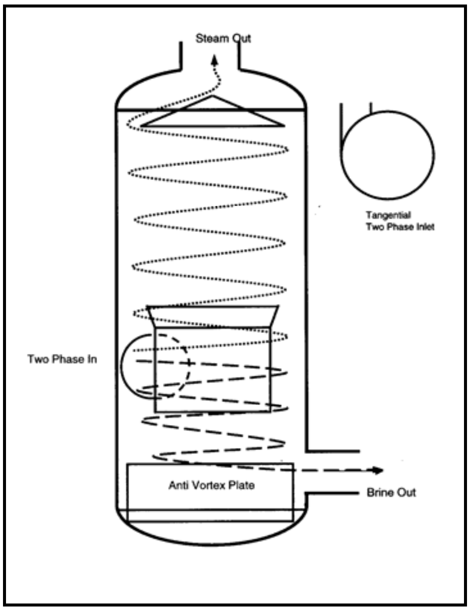

Figure 3 – An Early Separator Design

3. THE WEBRE TYPE SEPARATOR

In 1961, Bangma ran a series of experiments with separator configuration and came to the conclusion that a separator with a spiral inlet is more efficient than a tangential inlet. By progressively increasing the inlet velocity of the separator, he also demonstrated that the separation efficiency increases until a breakdown velocity (Figure 4) is reached. Above this velocity, the efficiency deteriorates rapidly. He noted that the spiral inlet separator has a higher inlet breakdown velocity than the tangential one (about 60% higher). His spiral inlet separator achieves the highest efficiency when the steam inlet velocity is between 30 and 40 m/s. The breakdown velocity is approximately 45 m/s. Current separator design is based on this 1961 model.

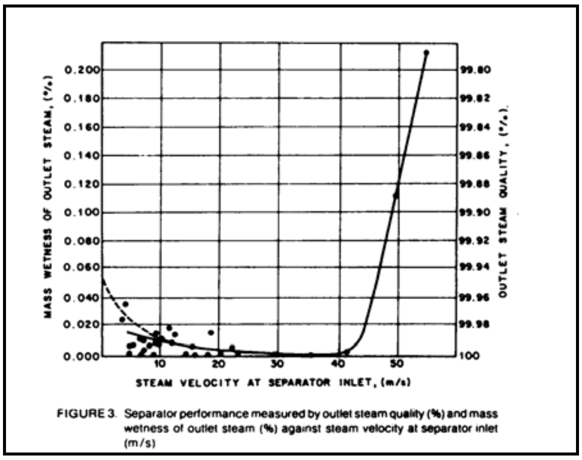

Figure 4 – Break Down Velocity

There are some variations to the Webre separator design. Following are three such variations.

The first one has plates at the two-phase inlet to presumably direct flow downwards at a fixed pitch for the spiraling fluid. This does not happen in practice and these plates will probably obstruct and interrupt flow, causing brine to splash inside the separating chamber (Figure 5).

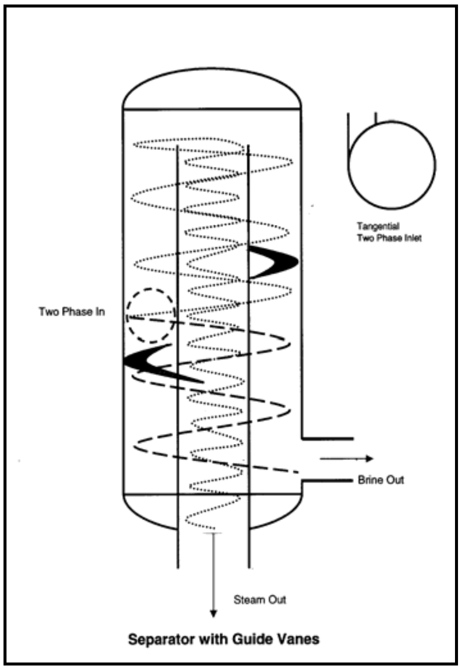

Figure 5 – Separator with Guide Vanes

The second one has the two-phase inlet at the top, the steam tube in the middle and the brine pipe at the bottom. (Figure 6). The baffle plate at the top of the steam tube presumably "cuts" the steam from the brine, which continues downwards to the bottom of the vessel. Such a configuration would assume that the steam/brine ratio is fixed for the life of the plant and the size of the baffle plate sized accordingly

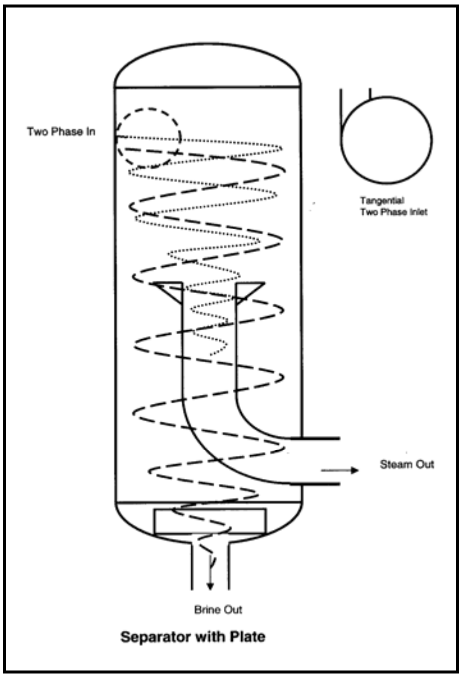

Figure 6 – Separator with Baffle Plate

The third one has a spiral inlet with a constant curvature and a small downward angle on the inlet to encourage brine to spiral downwards (Figure 7). Once inside the vessel, the fluid is left to find its own equilibrium unobstructed. It is very similar to the one tested by Bangma in 1961.

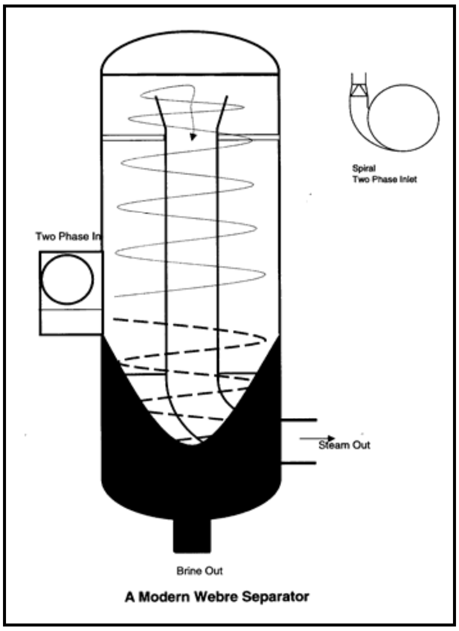

Figure 7 – Separator with Spiral Inlet

The design familiar to the author has a rectangular spiral inlet with a constant change in curvature over a 90 degrees flow path. The scroll like inlet has the fluid subjected to an increasing centrifugal force and "lays" the water film on the vessel wall as it enters to minimize the "splash" that high velocity brine makes when it comes in contact with a curve surface. It also has a sloped bottom that directs the brine in a downwards spiral. Very high efficiency is achieved with this design. Mechanical separation efficiency is probably as good as it can be. Further improvements may be possible by optimizing the aspect ratio of the inlet, slope and inlet velocity. But these probably require extensive laboratory testing and would vary with fluid conditions. But fluid conditions vary with the life of a geothermal resource so it is impossible to define what these are.

4. CURRENT SEPARATOR DESIGN EXPERIENCE

The sharp inlet coupled with 180 degrees reversal of flow and very high angular velocity contributed much to the pressure drop across the separator. This varies from 0.3 to 0.5 bars depending on the design.

One separator inspected showed failure in the steam tube at two areas. The point where the steam tube is welded to a baffle plate inside the separator and the area around the inlet to the steam tube. Both were thought to have been caused by the forces generated by spiraling fluid.

The fatigue cracks on the welds attaching the tube to the vessel baffle plate suggested that the swirling flow of steam had caused the steam tube to behave like a whirling shaft (Figure 8). It is thought that similar forces also cause the inlet to "ovalate" (Figure 9), going from round to oval shape and vice versa. This is inspite of the inlet being reinforced with a steel collar.

To overcome the problem, the inlet was reinforced to make it more rigid and the tube was supported by struts welded to the vessel wall. The latter obstructed steam flow. The effects of this obstruction cannot be quantified but it is likely to cause turbulence leading to entrainment of fine water droplets.

In later design, a pipe reducer was installed at the steam inlet. This makes the inlet more rigid and it also acts like a cheap "flared" inlet. This innovation worked and the pressure drop across the separator shows an improvement.

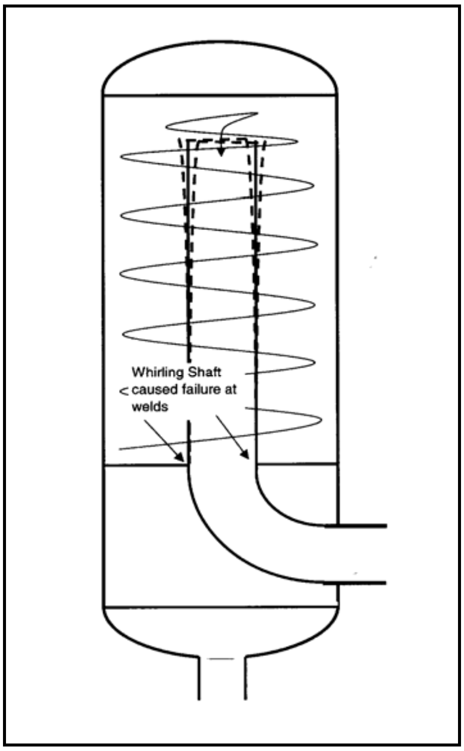

Figure 8 – Whirling Steam Inlet

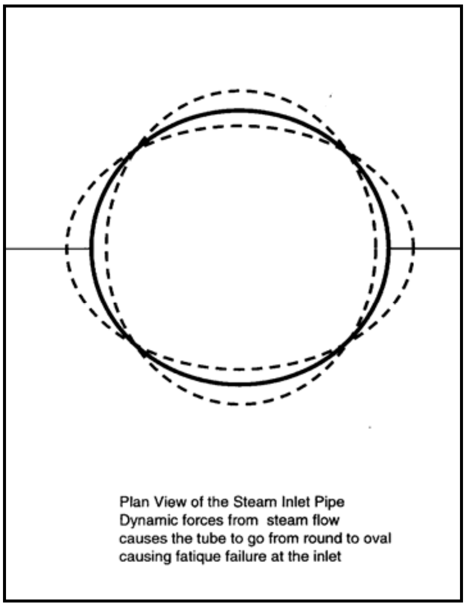

Figure 9 – "Ovalation"

5. SEPARATOR EFFICIENCY

In 1984, Lazalde-Crabtree presented a paper on the Design Approach of Steam Water Separators. The paper stated that Separator efficiency is measured by the amount of brine carry over into the steam. This definition has been "universally accepted" as the way to measure separator efficiency. Lazalde-Crabtree also proposed that the efficiency of separator is a product of mechanical and annular efficiency.

$$\eta_{ef} = \eta_m \times \eta_A$$

η_m = Centrifugal efficiency

η_A = Annular efficiency

The former is function of centrifugal forces and the latter deals with entrainment of water droplets in the annular space between the outer wall and the inner steam tube. It is related to the terminal velocity of the water droplets and the vertical steam velocity inside this annular space. "Settling efficiency" is probably a better term to use than annular efficiency.

I believe it is more appropriate to express the efficiency, using the same terminology as follows:-

$$\eta_{ef} = \eta_m + x(1-\eta_m)\eta_A + y(1-\eta_m)\eta_B + z(1-\eta_m)\eta_C + \ldots$$

where (x + y + z +..) =1 and holds true only if "parallel" separation mechanisms occur after the initial separation.

In a liquid dominated system, most of the brine is separated by centrifugal forces when the fluid enters the separator. This could be as high as 95%. The balance of the brine, small amount, is separated in a different part of the vessel by different mechanism(s). The second term represents the efficiency contributed by the annular or settling efficiency described in Lezalde's equation. If this is 100% and x = 1, the separator efficiency is 100%.

If only the first two terms are considered and x=1, high efficiency can be achieved in a knock out drum when mechanical efficiency is low but settling separation efficiency is high. However, a very large knock out drum is required.

The third and subsequent terms are left in the equation to allow for other mechanisms of separation after initial separation. This equation needs further investigation as sequential separation mechanisms require it to be written quite differently.

The separation efficiency achieved by the Bangma type Webre separator is in the order of 99.9% and would be quite sufficient for most processes. However in geothermal power application, the cumulative effects of small brine carry over with associated dissolve chemicals can be quite large. For example in a 100 MW plant, the steam flow required is in the order of 800 TPH. Even with separator operating at 99.97% efficiency, the amount of brine carried over into the steam line is 0.24 TPH. A 0.01% improvement will reduce brine carry over by 0.08 TPH.

The following picture (Figure 10) shows blocked holes of a diffuser connected to the steam line downstream of a Webre separator with efficiency of the high 99%! Turbines with steam scrubbers and steam wash facilities are reported to also have silica deposition problems.

Figure 10 – Blocked Diffuser Holes

Therefore, whatever efficiency can be gained, no matter how small, will improve the steam quality leaving the separator and will cause fewer problems in the steam system and the turbines in the power plant.

6. FLUID BEHAVIOUR INSIDE THE SEPARATOR

Two fluid behaviors are considered in this section.

6.1 Wall Creep

The steam moving up to the inlet of the steam tube picks up tiny water droplets. As it spirals upwards, the centrifugal force moves these water droplets radially from the center of the vessel to the outside wall. If the straight section is tall enough, there maybe enough time for the droplets to reach the vessel wall and coalesce with others to form a water film. If this film is too thick, water will peel off the film and drops back into the vessel to rejoin the rest of the brine flowing out of the vessel. However a small thin film of water will continue to flow in the general direction of the steam and moves up the vessel (Figure 11). When it reaches the top, the roof of the vessel, it will coalesce and fall from the underside of the roof into the steam outlet pipe.

A similar film will cling to the outside wall of the steam tube, move up and flow into the steam tube.

This mechanism where water creeps up a wall in a spinning fluid is quite well known especially in industries where centrifuges are used.

Pollak showed in his experiments with cyclones that the water in the outlet steam is mainly due to entrainment and to the creep of water film up the cyclone walls. Ter Linden tried to overcome the entrainment problem due to wall creep by introducing a skirt, a concentric annular ring, at the top of the vessel to trap the water (Figure 12). This probably did not improve the situation, as the water would still drop into the steam flowing out of the cyclone separator.

The water really needs to be trapped and led away from the main steam flow.

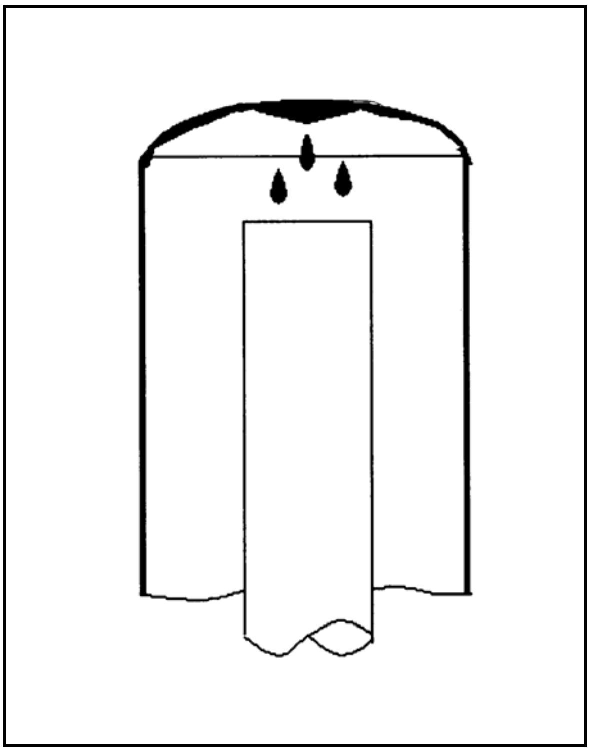

Figure 11 – Wall Creep

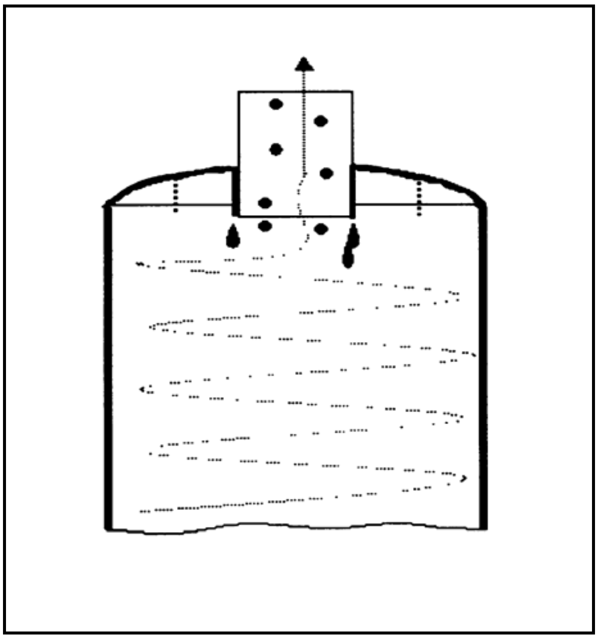

Figure 12 – Annular Ring to Trap Water

6.2 Conservation of Momentum

The tangential velocity of a spinning fluid near the wall of the vessel is the product of radius and angular velocity (V = ωr). By the conservation of momentum, ω increases as the steam moves from the wall to the center where the steam outlet is located. Therefore the fluid spins faster near the steam outlet. The centrifugal force being a function of the radius and the square of the angular velocity ($r\omega^2$) is large near the center of the steam outlet (Figure 13). A drop of water falling into the center of this spinning fluid will be shattered. Some fluid particles are flung radially outwards to the wall. One can imagine the many fluid particles being moved out from the center of the Webre separator only to be to be recycled again.

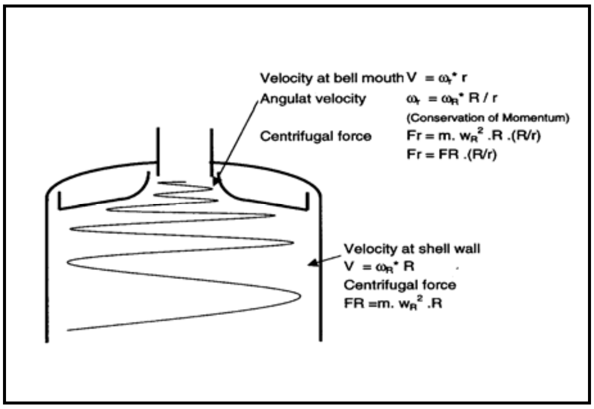

Figure 13 – Conservation of Momentum

7. PROPOSED MODIFICATIONS

With separator efficiency of 99.7% and some claimed 99.9%, it would be very hard to improve on it. However, it is felt that the wall creep mechanism described above is not adequately addressed by the current Webre design and it is believed that significant improvement can be made to minimize the problem.

A modification can be made to the Webre Separator by installing a plate under the roof of the separator and draining the collected fluid down the center of the steam tube to the main brine stream (Figure 14). The inverted “chinaman” hat could also improve the dynamics in the inlet and could possibly improve the pressure drop.

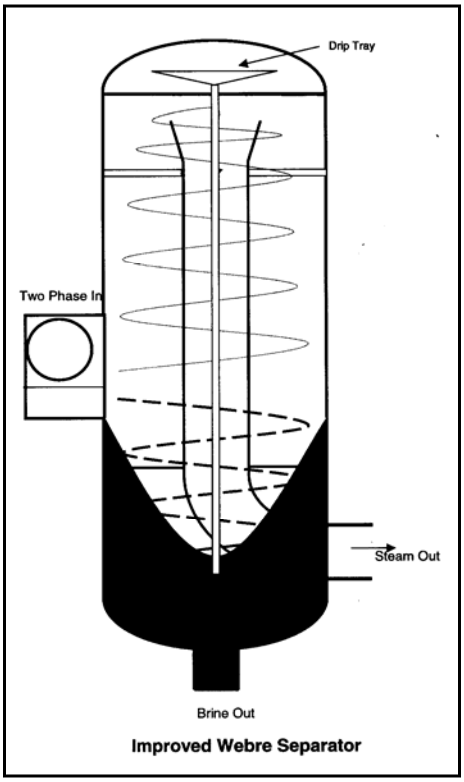

Figure 14 – Modification with Drip Tray

However a more radical change is proposed.

Back in 1961, Bangma gave two reasons for choosing the bottom outlet cyclone (BOC) separator over the top outlet cyclone (TOC) separator

1. No interior baffles and fittings
2. Steam removal from the bottom make simpler pipe work.

The first reason was given probably because the original TOC separator was a complicated design and had a lot of internal baffles. The second reason is debatable.

Changes proposed unfortunately take the conceptual design of the separator back to a top outlet unit.

7.1 Trapping Water

Central to the conceptual separator is a bell mouth inlet at the top of the separator (Figure 15). It is hung from the roof of the separator but not connected to the steam outlet tube nor the separator wall except for a tube connection. The position of the bell mouth inlet "close off" a space between it and the roof of the vessel, refer here as the trap space. It also forms two traps to remove water creeping up walls.

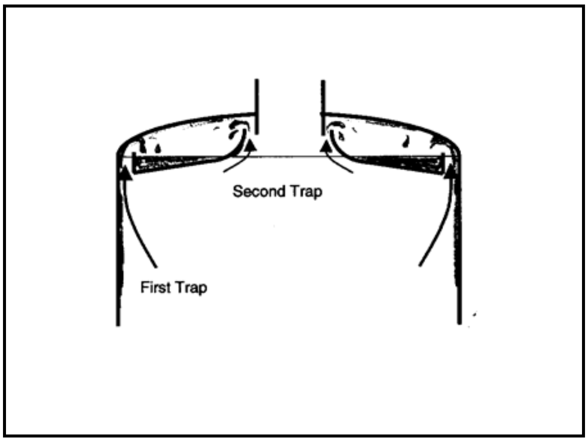

Figure 15 – Bell Mouth Inlet

As water creeps up the vertical section of the separator wall, it enters the trap space by its upward momentum. Inside the space, it follows the curve wall of the semi-ellipsoidal head. It soon loose its momentum and drop from the roof into a tray formed by the bell mouth.

Water that escapes this first trap may continue to creep up the face of the bell mouth against an increasing centrifugal force exerted by the spinning steam. If it does get into the mouth, centrifugal force will hold it to the side of the wall as it climb into a second trap formed by the smaller steam outlet and the bell mouth. This type of trap is commonly used in centrifuge to decant one product from another

Lowering the pressure slightly in the trap space may assist in trapping the water. It is quite possible, (experimentation is required) to create a slightly lower pressure in the trap space by ducting the trap space into the "vena contracta" of the expanding fluid in the separator inlet nozzle. Cooling the steam in this space has similar effect. Both need to be investigated.

The trapped brine is simply piped away to the main brine system.

7.2 Pressure Loss

The current Webre design has a sharp entry to the steam tube. The flow also does a very sharp 180 degrees turn before traveling down a straight steam tube to connect to a steam main.

Looking at just the entry to the point where steam starts traveling down a straight tube, it can be said that the pipe system in this short section (Figure 16) consist of:

- 1 x sharp inlet
- 2 x miter bends

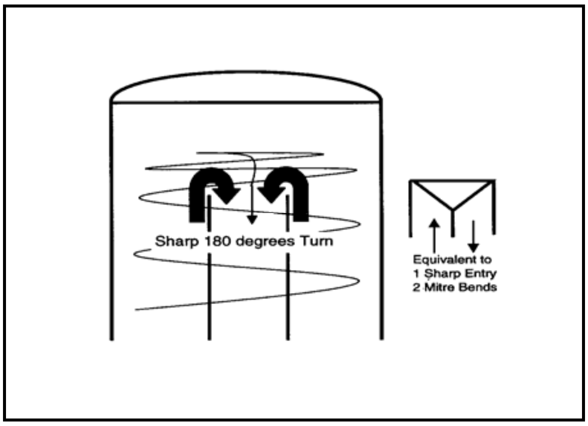

Figure 16 – Equivalent Inlet Loss of Webre Separator

Similarly, the piping system in the conceptual design (Figure 17) can be said to consists of

- 1 x bell mouth entry
- 2 x LR bends

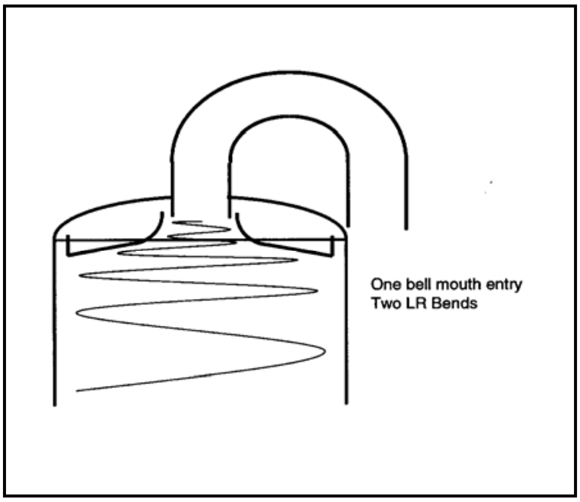

Figure 17 – Equivalent Inlet Loss of New Separator

One can immediately see that there is an improvement in pressure loss even without doing any calculation.

For an 18" to 20" steam outlet pipe, the total resistant coefficient (K factor in Crane) for the two configurations are 1.22 and 0.4 approximately or a ratio of 3:1.

If the pressure drop in the steam system can be lowered, the life of a geothermal well can be extended as separation can take place at a lower pressure. A typical well characteristic shows increase mass flow at lower pressure and the steam fraction for a given fluid enthalpy increases as pressure reduces. The result is more steam.

7.3. Settling Efficiency

With the center tube removed the cross sectional area for a given diameter separator available for upward flow is increased. This leads to lower upward velocity and would improve the settling efficiency.

One can of course reduce separator size to maintain the same upward velocity with theoretically no change in efficiency.

7.4. Accessibility

Inside the Webre separator, the internal steam pipe is located in the middle of the cylindrical shell of the separator leaving a very small annular space between them. Part of the maintenance requirement is to inspect the internals of the separator for weld cracks, wear and debris accumulation

An operator using the manhole to access the Webre separator is immediately confronted with the steam tube directly in front. Generally, peering into the separator is all that can be done to inspect the separator. In a larger diameter separator, the operator might be able to squeeze into the annular space between the vessel wall and steam tube.

With the steam pipe removed from the center of the separator, it opens up the space inside the separator and inspection is made much easier. It also reduces the available wall area for water creep

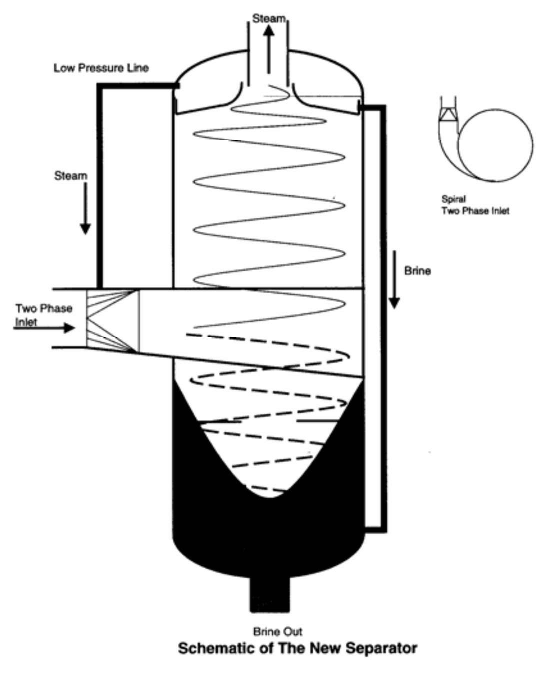

Figure 18 – The Concept for a New Separator

8. CONCLUSIONS

The problem with water creep was re-cognized by Pollak and Ter Linden but not addressed in current separator design. The efficiency equation proposed by Lazalde-Crabtree certainly did not recognize it

The conceptual separator recognized this problem and a third term is required in the proposed efficiency equation to account for this. In addressing the problem improvements were made in other areas.

In summary, the anticipated improvements with this new design are as follows:

- Trap and reduce re-entrainment of creep water from the vessel wall
- Improve settling efficiency marginally by decreasing up draft velocity
- Reduce pressure loss in the separator.
- Significantly improve access to the inside of the separator

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