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SILICA SCALING UNDER CONTROLLED HYDRODYNAMIC CONDITIONS

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ABSTRACT

Silica scaling has been previously shown to be affected by hydrodynamic conditions. A pilot plant incorporating a water tunnel was built to investigate the effect of hydrodynamic conditions and silica colloid particle size on the rate of and style of silica scaling. In the water tunnel, fluid flow and silica colloid particle size can be controlled. Development and design of the test rig is described. Tests using vertical flat plates and vertical cylinders have been conducted. We believe that flat plate results are affected by bacterial deposition, but the vertical cylinder experiments show a definite hydrodynamic and particle size effect. Ultimately, the aim of this work is to characterise the link between fluid flow characteristics, silica colloid particle size and the scaling process, and to thereby understand the fundamental processes involved in silica scaling in geothermal systems.

1. INTRODUCTION

Silica dissolved in geothermal fluids can cause severe scaling problems, placing a major constraint on fluid utilisation in some geothermal operations. The formation of silica scale in pipelines, heat exchangers, and reinjection wells is common where geothermal fluids are supersaturated with silica.

After steam extraction or fluid cooling the likelihood of precipitation of dissolved solids increases. In fluids supersaturated with respect to amorphous silica the mechanism responsible for the majority of silica deposition is the preliminary formation of colloids and their subsequent precipitation on to equipment surfaces, as a voluminous, sometimes hard, but often porous scale. This scale causes reduced heat transfer in heat exchangers, increased pressure drop in pipes and, in severe cases, can cause complete blockages in sections of the system.

Any reduction in the scaling rate will allow higher steam fractions or larger temperature drops before problems occur, resulting in more efficient use of geothermal resources.

Although silica scaling is a widely observed problem in geothermal operations the actual mechanism by which the silica colloids are transported to the scaled surface from the bulk fluid is not well understood at a molecular level. The experiments and equipment described in this paper have been set up with the objective of obtaining a more fundamental understanding of the silica scaling mechanism as it applies to geothermal equipment.

1.1 Previous work

There is a large literature on the nature of silica colloid formation and growth. (eg Fleming 1986, Brown & McDowell 1983). This work has primarily emphasized the polymerisation kinetics of silica, and the effects of pH, other ions in solution, temperature, and degree of supersaturation on these polymerisation kinetics. Consequently, although there is not yet sufficient data to confidently predict an exact polymerisation curve, the general principles are known. However, relatively little research has been undertaken to investigate hydrodynamic effects on silica scaling.

It has been empirically observed that the fluid flow structure can influence silica scaling. Unusual scaling has been observed near bends, valves and other items which disturb or disrupt the flow. Some years ago a simple experiment to determine the hydrodynamic influence on silica scaling was conducted in the waste water drains at Wairakei (Garibaldi, 1980). Two cylinders and a horizontal flat plate were exposed to the flow for several weeks, providing qualitative evidence that fluid hydrodynamics played an important role in the deposition process. However, the flow conditions within the drain were difficult to characterise and this placed a limitation on the interpretation of the results.

Garibaldi (1980) observed higher rates of silica scale growth in areas of low fluid velocity. The stagnation point at the front of an exposed cylinder, for example, showed a high rate of deposition. Less silica was observed at points 90° to the flow axis, where the velocity is highest. The morphology of the silica scale was also dependent on the fluid flow, with cellular silica structures in areas of recirculation and more needle like structures in well directed flow. Distinct zones of deposition were also seen on the flat plate, and these appeared to relate to laminar, transitional and turbulent flow regions.

Another study, related to this current work, has been reported (Pott et.al., 1996. In this study the deposition of silica onto a flat plate in laminar flow was modelled numerically. Attractive forces acting between particles and the plate were modelled at the same time as the fluid flow, using a finite difference method. This work indicated that deposition rate was dependent on particle size, with small particles depositing more quickly, and that deposition would initially be highest at the front of the plate. It was predicted that an initial build-up of silica scale at the front of the plate would change the shape of the laminar boundary layer. This could lead to flow separation and an earlier transition to turbulent flow, hence increasing colloidal deposition.

2. APPLICATIONS AND OBJECTIVES

The current work attempts to identify the effects of flow characteristics on scaling by controlling both silica colloidal particle size and fluid flow conditions simultaneously. The hydrodynamically well examined and prescribed geometry of a flat plate in parallel laminar flow was the first flow situation to be investigated followed by a vertical cylinder. It is hoped that the work will lead to a fundamental understanding of the forces involved in an individual colloid particle moving from the bulk solution phase and becoming attached to the wall.

2.1 Geothermal examples

If a fundamental understanding is gained from this study, it could lead to an ability to predict those positions within geothermal engineering plant that will have a likelihood of severe silica scaling. Conversely, it is hoped that this work will lead to design parameters that can mitigate silica scaling in geothermal applications.

2.2 Epithermal mineral deposits

It is now realised that the gold and silver epithermal ore deposits such as those found in the Coromandel region of NZ are extinct geothermal systems. (White, 1981, Brown, 1986). In these systems, the gold and silver mineralisation is normally found in quartz veins. This quartz was almost certainly deposited as colloidal amorphous silica. An understanding of the particular fluid flow and colloid characteristics during deposition of the gold bearing veins could shed understanding on the deposition process, and lead to better exploration and development of these types of ore deposits.

3. DESIGN OF THE TEST SYSTEM

3.1 Experimental conditions

The objective of this work was to create a well controlled environment in which the influence of both hydrodynamic conditions, and silica colloid particle size, on the growth of silica scale could be observed. The test conditions had to relate as closely as possible to conditions in geothermal reinjection systems, since this is the predominant location for silica scaling problems.

Controlling the silica colloid particle size and providing well controlled hydrodynamic conditions were considered the primary objectives. A method for achieving control over these parameters then had to be identified.

3.1 Flow condition requirements

In order to provide a well characterised hydrodynamic flow the water tunnel had to meet several specific requirements. The tunnel test section had to be large enough that the models placed within it would not seriously impede the flow. This restriction limits the model cross section to around 10-15% of the tunnel area. A minimum practical dimension for instrumented test cylinders, bars and the like was accepted as around 25mm, implying a tunnel diameter of 200mm: This was the dimension chosen for the test section.

To adequately reproduce the flow conditions found in geothermal situations it was desirable to have the capability to test at a range of velocities from 0.5m/s to 3m/s. With a 200mm diameter test section this required a geothermal flow of 56 to 336 tonne/hr. A uniform velocity profile across the test section was also required. Because such a large quantity of geothermal fluid was required to produce the flows in the test section, a once through system was considered impractical due to the pre-treatment required to ensure controlled growth of silica colloids. Consequently, a design was proposed where treated fluid is recirculated using a pump. A small fraction of the recirculated flow is drawn off from this circuit (between 2-10t/hr) and is replaced by freshly treated geothermal brine.

The make up fluid is not required to replace silica, but is to ensure that any trace components which may play a role in silica deposition are replenished. The average residence time for treated fluid in the recirculating loop that was eventually fabricated is between 7 and 35 minutes, depending on the make up flow rate. A schematic of the test system is shown in Figure 1.

3.2 The test section

A uniform velocity is desired across the test section (ie no pressure gradient across the flow), to provide constant conditions across the entire width of the test piece. This was achieved by allowing the fluid to settle in a 500mm diameter pipe (at low velocity) and then accelerating the fluid quickly into the test section. Standard pipeline reducers were used to step down from the 500mm pipe into the 200mm test section. A great deal of care was taken during assembly of the rig to ensure that the nozzle provided a smooth transition. All welds were smoothed on the inside of the nozzle and spigoted flanges provided precise alignment without the need for gaskets.

Provision was made to insert and secure models and test plates in the test section by including four large (50mm diameter) access ports at 90° spacing around the perimeter. Ten smaller access ports (12mm diameter) were included in two planes along the axis of the test section to provide access for a pitot-static probe. All of the access port plugs were smoothed to conform to the inner wall of the test section to prevent disruption of the flow. A window was initially installed in the test section to allow observation of the scaling process, but this was later abandoned.

3.3 Silica particle size

Silica particle size control was obtained by manipulating the nucleation temperature. The particle size distribution was monodisperse, typically with a standard deviation of ~ 6nm. A plate heat exchanger provided initial cooling of fluid from the Wairakei reinjection line. This fluid was then passed to a hold up tank to allow for silica particle growth to stabilise at the required size and then the fluid was passed into the recirculating section of the plant.

3.4 Controls and instrumentation

Flow control was achieved using a valve mounted near the pump discharge. This valve was sized to allow flow control between 0.5-3.0m/s in the test section with 20-70% opening. An electric valve actuator was used to modulate the valve setting, based on the differential pressure between the settling section and the entry to the test section. This differential pressure was measured using a pressure transducer. The pressure signal was passed to a programmable logic controller, which provided the valve modulation signal. Use of this control arrangement allowed a constant velocity to be maintained within the test section even if silica scale were to significantly alter the pressure drop in the recirculating loop during the test.

Local dynamic pressures and temperatures within the test section were also measured. In this case the transducer was connected to 4mm diameter AIRFLOW pitot-static tube which could be inserted through any one of the twenty access ports in the side or top of the test section.

4.0 RESULTS

Initial tests

Commissioning tests were performed with no samples installed in the rig. These tests confirmed that the velocity profile in the test section was sufficiently uniform and that additional flow straighteners would be unnecessary. A typical velocity profile obtained during these tests measured with a traversing pitot-static tube is shown in Figure 2.

The first test specimen was a stainless steel plate of 100mm length, sharpened to a knife edge at the upstream end. This plate was exposed to a flow velocity of 1.2m/s and a silica particle size of approximately 8.5nm for a period of 20 days. Very little scaling was observed on this plate, and certainly none of the voluminous silica scaling normally associated with geothermal applications. The dimensions of this test plate were the same as those used by Pott et.al. (1996) in their numerical simulations.

This test confirmed that the plate mounting method was performing satisfactorily and that the control system could provide constant flow conditions throughout the test.

The absence of visible scaling on this plate is consistent with previous experiments that had shown that very small particle size colloids display very low scaling rates. This is in contrast to the theoretical results deduced by Pott et al. It was also thought that the short length of the plate (100mm) may not provide sufficient length for a transition region to develop within the boundary layer and it was expected that scaling may be more pronounced on a longer plate.

Changes to the test plates

After the first test the plate design was modified. Subsequent plates were 250mm long, made of mild steel, and included, on one side of the plate only, a trip wire 5mm behind the sharpened leading edge. The purpose of this wire was to cause the boundary layer to become turbulent, so that a comparison could be made with the naturally developing laminar boundary on the other side. As well, the particle size was increased to increase the likelihood of scaling. At this stage, we believe that there is significant free stream turbulence which influences the flow over the test specimens. (Dunstall et al, These volumes)

A series of tests was conducted with the new plates, to cover a range of particle size and flow conditions. This series of experiments is set out in Table 1.

The flat plate tests were designed to cover the four options of smaller and larger particle sizes together with lower and higher flow rates. The flow rates were able to be well controlled, but the particle size control was somewhat variable. There were also some mechanical problems with the plant, and with the supply of reinjection water from the borefield.

Results obtained with the new plates were encouraging but also a little unexpected. Test 2, the first test with the trip wire and the mild steel plate, produced an unexpected result. Little scaling was seen over the first 40mm of plate length with substantial scaling further downstream. Both sides of the plate had the same appearance (ie. no noticeable effect due to the trip wire); and the plate showed considerable scaling whereas the inside of the pipe in the test section appeared clean. Test 3 was conducted using plate material sourced from a different supplier to plate 2. This plate gave quite different results, with much less scaling - in fact, no noticeable scaling at all.

At this time it became clear that Test 2 was showing unusual behaviour and a query revealed that the mild steel had a very thin coating of sprayed zinc for protection. This coating had been partly removed when the knife edge was machined and, in this area, little scaling had occurred. Where the zinc remained intact, the scaling was much heavier. The untreated carbon steel walls of the pipe test section that were coated with normal mill scale remained relatively silica free. In order to confirm that the zinc was responsible for the greatly increased scaling rate the samples installed in all subsequent tests had the zinc coating removed from half of the plate on both sides. Test 4 was the first test performed in this way, and confirmed that the presence of zinc on the surface greatly increased the rate of silica scaling.

Despite changes to the velocity and particle size in subsequent tests there was no observable influence of hydrodynamics in the scaling process.

The morphology of the silica scale deposited in these later tests was rather unusual. When fresh, the scale exhibited a filamentous structure, which appeared to be soft and flexible.

Moreover, the weirbox, which was also zinc plated, grew a very profuse, soft, filamentous scale. After drying, the scale became hard and inflexible - very similar to scale observed inside pipe lines. It is proposed that the precipitation of this scale was being mediated by thermophilic bacteria. Previous work (Cady et.al. 1998) has shown that these bacteria exist in the geothermal systems, and they are apparently easily colonised by air transfer. It would appear that the zinc is required somehow in their metabolism or that the Zn changes the surface properties.

Although it is rather hard to quantify with the experiments having variable length of exposure, there appears to be a correlation of scaling rate with particle size. The smaller particles cause less scaling than the larger particles. Whether this has been an effect of the microbial control, we were not able to discern at this stage.

Vertical cylinder tests

A series of vertical cylinder tests followed the flat plate experiments. Flow over a cylinder has been extensively studied. In our experiments, we used a vertical orientation, as opposed to Garabaldi (1980) who examined flow over a horizontal cylinder. The turbulent flow around a cylinder expected in our tests is shown in Dunstall et al (2000). The mild steel cylinders were 25mm in diameter, and sized to fit exactly across the whole diameter of the test section. Six experiments were completed with these cylinders. These covered the variables of a large (~120nm), medium (~70nm) and small (~15nm) particle size, together with a fast (~2.5m/s) and slow (~1m/s) fluid velocity. All of the cylinder experiments were for approximately the same time of about three weeks. None of the test sections were zinc coated in order to try to reduce any biological influence.

The results obtained in the cylinder experiments were different to the plate tests. The scales deposited were much harder than those observed for the flat plates, and a hydrodynamic influence was immediately obvious. Most striking was that no visible scaling occurs along the whole length of the stagnation line (Figure 3). This clear area was about 3mm wide. The silica free area on the stagnation line was wider for lower velocities with the same particle size and also slightly wider for smaller particles at the same velocity. On either side there was an area of "picket fence" silica scaling, with the "fences" being parallel to the length of the cylinder, or perpendicular to the flow stream lines, and pointing into the flow. This type of scaling was evident from the edge of the stagnation line, to a point about 90^o around the cylinder from the forward facing side. The back half of the cylinder, which was facing away from the flow direction was essentially free of scale.

There was also a very marked effect due to particle size. The larger the particle size, the greater the degree of scaling. Silica scaling at the smaller particles sizes was almost non existent (Figure 4).

The scales deposited on the cylinders are much more like those commonly seen in geothermal fields than the scales observed on the flat plates. Higher temperatures were used in these experiments (> 65^{o}C), and the samples were zinc free. We believe, therefore, that the vertical cylinder scaling is not biologically mediated.

Compared to the cylinder tests described by Garibaldi (1980), there are some similarities, and some differences. Garabali described needle-like structures in areas of well directed flow. We describe "picket fences" in the same regions. However, Garabaldi observed high scaling rates in the stagnation line, whereas we see a complete absence of scaling. In addition, Garabaldi observed cellular structure in the zone of recirculation (on the downstream 180^o of the cylinder), while we observed no scaling here. In our tests, it appeared that the area in between the picket fences had started to fill in with more porous material. If the samples had been exposed for longer, then they may have started to look similar to those of Garabaldi.

We were not able to discern any difference in silica scaling between either end of the cylinders, which indicates that there is a negligible gravity effect in these experiments. Where the flow was disturbed close to the test tunnel walls, the silica scale was aligned in a "horse-shoe" pattern, again indicating that it was forming perpendicular to the flow stream. The micro characteristics of the silica scale have been investigated further in another paper (Dunstall et al 2000).

5. 0 DISCUSSION

There is a definite colloid particle size effect, and a definite hydrodynamic effect observed in the cylinder tests. These are considered to be more representative of the general geothermal silica scaling since they are presumed to be abiotically deposited. They are also more similar to silica scale observed in many geothermal fields.

Silica scaling occurs at a micro level only when a colloid is transported from the bulk fluid to a scaling surface. This will require transport of the colloid through the boundary layer adjacent to the surface. A number of different mechanisms are possible for this transport process. There could be:

- electrostatic forces
- diffusion forces
- inertial forces
- gravitational forces

Electrostatic forces arise because the silica colloids have a negative surface charge. However, calculations show that the electrostatic forces are likely to be too small over the distances (~0.5mm) to be traveled by the colloid.

Diffusion forces are set up by the concentration gradient dc/dx. The solution concentration of colloids at the surface is zero, and is a maximum in the bulk fluid. The diffusion force should be greatest for the smaller particles as they have a higher concentration. This is the opposite to the effect observed. Also, the boundary layer (x) is thinner at higher velocities and consequently, the amount of scaling should be greater at higher velocity. This is not observed either. Consequently, it seems unlikely that the transport process is diffusion controlled.

We saw no difference between the upper and lower surfaces of the cylinders, so we suspect that gravity is not important in this process at least, although often with very large particles and very small flows, gravity forces could be important.

The idea of an inertial penetration of the boundary layer is suggested by the very large particle size effect. Individual colloid particles will have a velocity distribution in the fluid due to Brownian motion. If the momentum is sufficient, the particles can penetrate the boundary layer to attach to a surface. The effect will be proportional to the mass and velocity of the particles. The mass of a colloid particle is proportional to the particle radius cubed, and so there should be a very large particle size effect, which we do observe. This would also explain the smaller silica free stagnation line at higher velocities.

6.0 Conclusions

It is suspected that the presence of bacteria is having a major influence on the results of at least some of the experiments. The source of these bacteria is currently being investigated. It appears that zinc somehow enhances bacterial deposition.

In the cylinder experiments, which are considered to be typical of geothermal silica scaling, there is a definite hydrodynamic effect which is manifested by the lack of scaling in the stagnation line and in the wake area of the cylinders. There is also a pronounced particle size effect. These observations are consistent with an inertial transport mechanism through the boundary layer.

7. ACKNOWLEDGMENTS

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Figure1 A schematic of thePilot plant

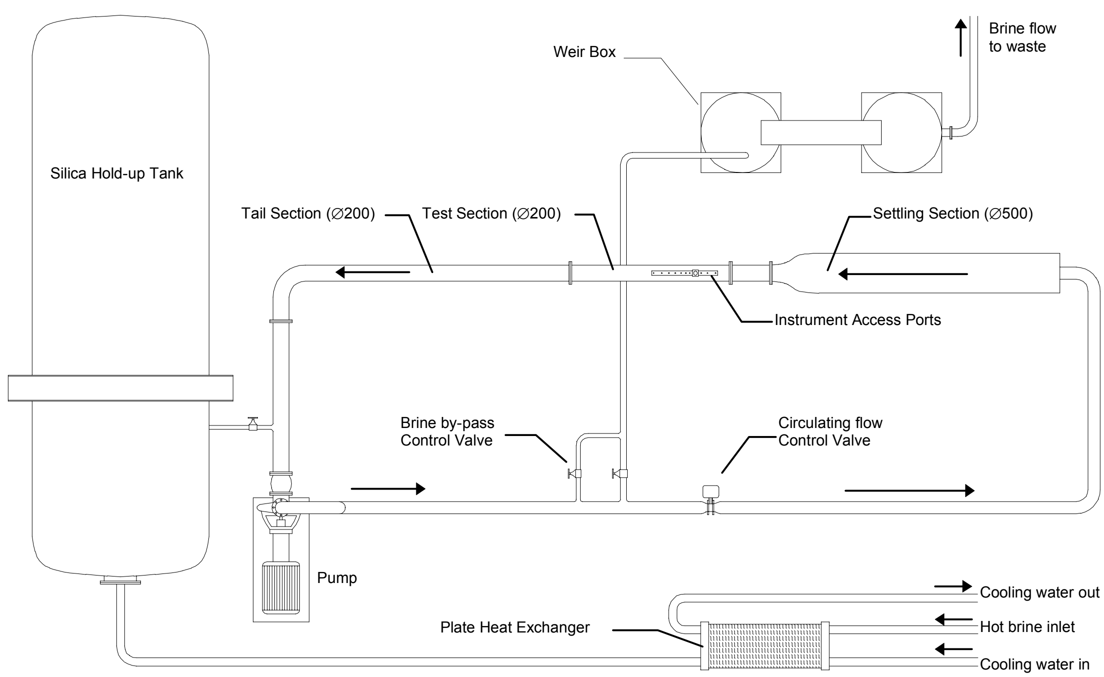

Table 1 - Flat plate experimental program

Tes	Silica size	Velocity	Duration
2**	50 nm	1.2 m/s	14 days
3	22 nm	1.2 m/s	31 days
4	29 nm	1.2 m/s	17 days
5	34 nm	2.0 m/s	15 days
6**	35 nm	2.0 m/s	<7 days
7**	Not measured	2.0 m/s	<7 days
8	12 nm	2.0 m/s	43 days
9**	95 nm	1.0 m/s	8 days

** = experiment halted early due to problems in the plant, in some cases before measurements could be obtained.

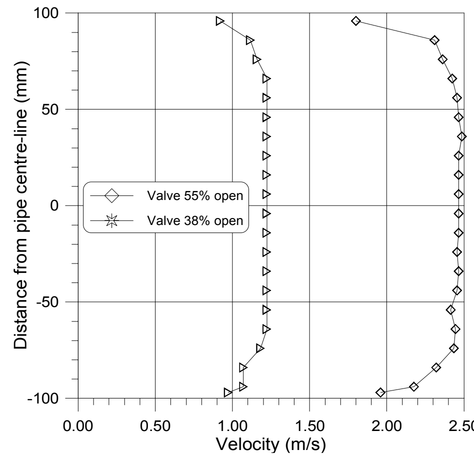

Figure 2. Velocity profile across diameter

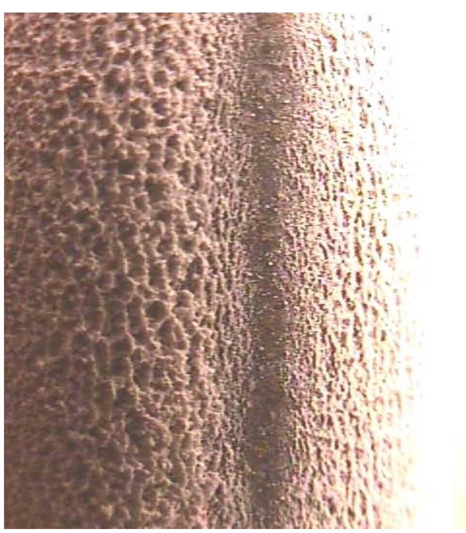

Figure 3 The stagnation line showing no silica deposition

Figure 4 The six trial cylinders. From L to R, large particles, low velocity; large particles, high velocity; medium particles, low velocity; medium particles, high velocity; small particles, low velocity; small particles, high velocity