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SILICA SCALING UNDER CONTROLLED HYDRODYNAMIC CONDITIONS: VERTICAL FLAT PLATE AND VERTICAL CYLINDER TESTS

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ABSTRACT

Silica scaling on the surface of a flat plate and a vertical cylinder has been investigated in a water tunnel, where fluid flow and silica colloid size conditions can be controlled. Development of the test rig is described and some preliminary results are presented. 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.

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 formation of colloids and their subsequent precipitation on to equipment surfaces, as a voluminous, sometimes hard, scale. This scale causes reduced heat transfer in heat exchangers, increased pressure drop in pipes and, in severe cases, can cause complete blockages in parts 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 is not well understood. 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.

Previous Work

There is a large literature on the nature of silida colloid formation and growth (eg Fleming 1986, Brown & McDowell 1983). This work has primarily emphasised 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 are 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 that 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 horizontal cylinders (axis perpendicular to the flow) and a flat plate (horizontal to the flow) were exposed for several weeks, providing qualitative evidence that fluid hydrodynamics played an important role in the deposition process.

Higher rates of silica scale growth were observed 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. However, the flow conditions within the drain were difficult to characterise and this placed a limitation on the interpretation of the results.

Another study, related to our current work, was reported earlier (Pott et al., 1996). In this study the deposition of silica onto a flat plate in laminar flow was modelled numerically. 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.

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 to be investigated. Currently, a series of tests is being conducted using vertical cylinders since this is another well studied flow situation.

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.

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.

In relation to 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 light on the deposition process, and lead to better exploration and development of these types of ore deposits.

DESIGN OF THE TEST SYSTEM

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.

Flow conditions

In order to provide a well characterised hydrodynamic flow the water tunnel had to meet several specific requirements,

Blockage - The tunnel test section had to be large enough that the models placed within it would not seriously impede the flow, allowing the boundary layer to grow as it would in free stream conditions. 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.

Velocity profile - 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. The primary problem identified for the once-through concept was the pre-treatment required to ensure controlled growth of silica colloids. The heat exchangers needed for such a system would be extremely large and expensive. Consequently, a design was proposed where treated fluid is recirculated using a pump. **A** small fraction of the recirculated flow is drawn off this circuit (between 2-10t/hr) and is replaced by freshly treated geothermal brine.

The make-up fluid is not required to replace silica, of which only a very small percentage actually precipitates, but is to ensure that any trace components that may play a role in 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.

The main elements of the test system are shown in Figure 1 (below).

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 sample or test piece. This was achieved by allowing the fluid to steady 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 between the settling section and test section 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 with the inner wall of the test section to prevent disruption of the flow.

A curved window was also installed in the test section to allow observation of the scaling process. Unfortunately this window became crazed over a period of time and is no longer useful.

Silica particle size

Silica particle size control was obtained by manipulating temperature and time conditions. 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 silica particle growth to the required size. From here the fluid was passed into the recirculating section of the rig. A typical particle size analysis is shown in Figure 2. The particles range in size from 15nm to 70nm, with an average size of 23nm.

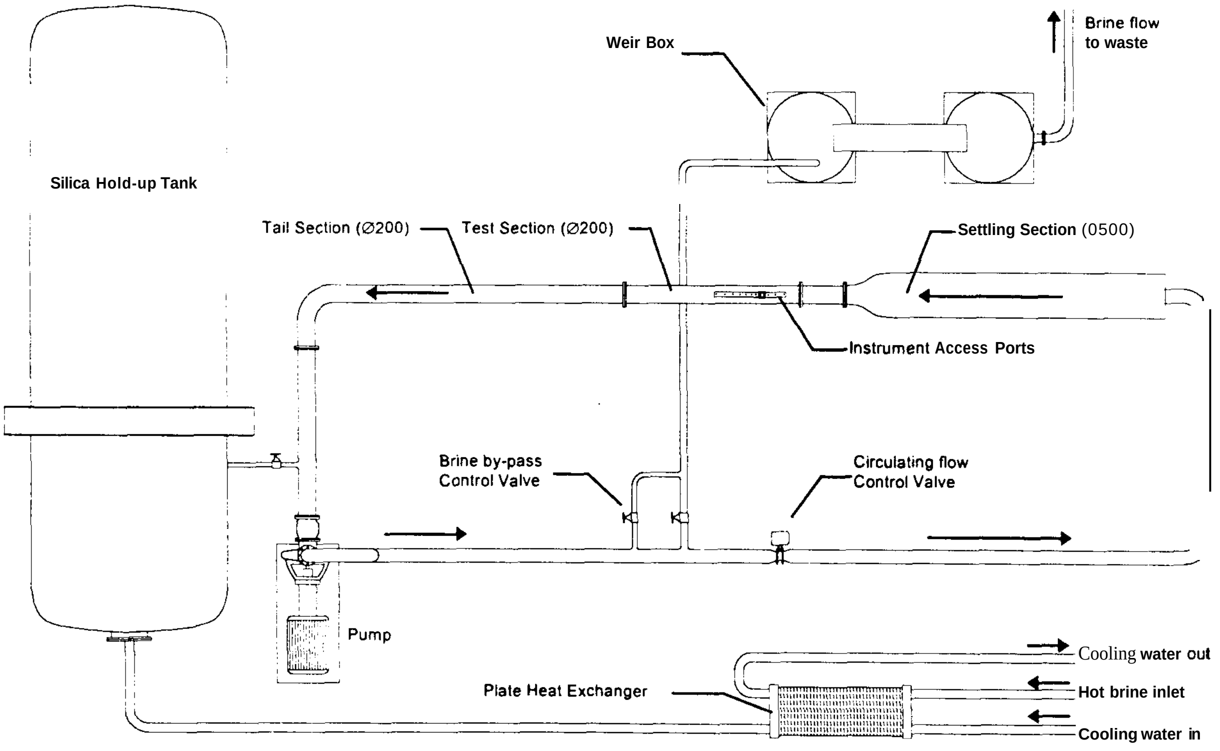

Figure 1 Recirculating test rig layout

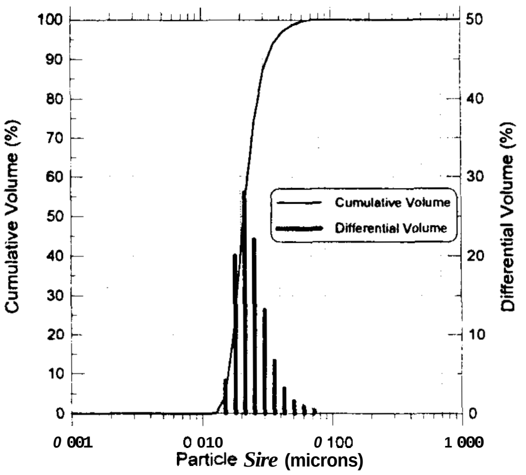

Figure 2 Silica colloid size analysis

Controls and instrumentation

Flow control was achieved using a butterfly 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 differentisl pressure between the settling section and the entry to the test section. This differential pressure was measured using a Rosemount 3051CD-2 pressure transducer. The pressure signal was passed to an ASCON **XS** series 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 be significant in the recirculating loop during the duration of a test.

Local dynamic pressures within the test section were also measured using a Rosemount pressure transducer (3051CD-1 model). 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.

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 3.

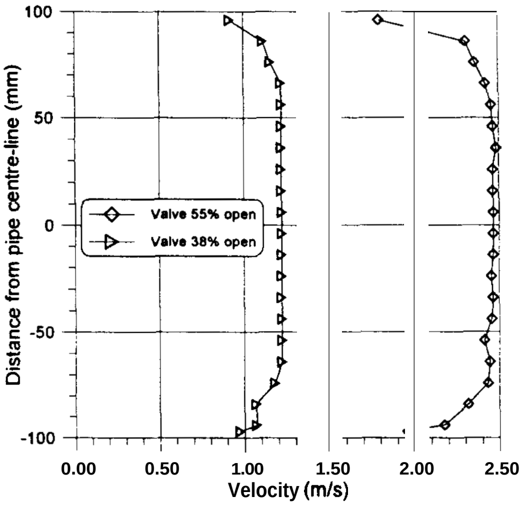

Figure 3 - Velocityprofile in the test section

The first test specimen was a stainless steel plate of 100mm length, sharpened to a knife edge at the upstream end and placed parallel to the flow. 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. The short length of the plate (100mm) did 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.

Installation and mounting of the short plate in the test section had proved easier than expected and the same methods could be applied to a longer plate with **no** anticipated difficulties.

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 layer on the other side. As well, the particle size was increased to increase the likelihood of scaling.

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

Table 1 - Flat plate experimental program

Test	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.

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 bore-field.

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.

In test 9 there is the possibility of a discernible zone of decreased scaling on the leading edge of the plate (both sides). This zone is approximately 1.5 cm long and could possibly be related to the flow phenomena.

Time constraints meant that Test 3 was performed using a plate sourced from a Taupo sheet-metal supplier, rather than the Auckland supplier used for plate 2. This plate gave quite different results, with much less scaling - in fact, no noticeable scaling at all on either side.

At this time it became clear that Test 2 was showing unusual behaviour and a query to the Auckland steel supplier 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, with the dividing line parallel to the flow. 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.

In experiment #8, the plate was found to be covered with a yellow deposit. This is assumed to be sulphur which was formed from H_2S in solution when the hold-up tank became contaminated with air during an emergency shutdown in the reinjection pipeline.

The morphology of the silica scale deposited in the later tests was rather unusual. When fresh, the scale exhibited a filamentous structure, which appeared to be soft and flexible. Moreover, the weir box, 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. Following examination by collaborative scientists from the exobiology unit at NASA, it was proposed that the scale being precipitated was mediated by thermophilic bacteria. Previous work had 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.

Special samples have been exposed in the test tunnel and have been recently sent to NASA for confirmation and identification of the microbial deposit.

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 cannot estimate.

Vertical cylinder tests

A series of vertical cylinder tests followed the flat plate tests. Flow over a cylinder, like flow over a flat plate, has been extensively studied and widely discussed in texts. In our experiments a vertical orientation was used, as for the flat plates tested thus far. Earlier work by Garibaldi (1980) examined flow over a horizontal cylinder.

A turbulent flow over a cylinder, similar to that expected in our tests, is shown in Figure 4.

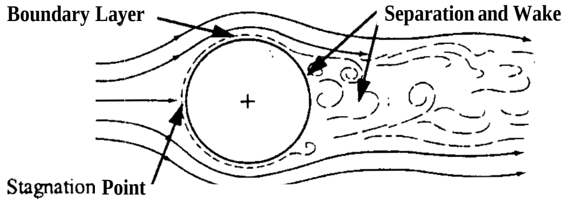

Figure 4 - Flow ***over a cylinder (White, 1979)***

The mild steel test cylinders were 25mm in diameter, 200mm long, and were radiused at each end to fit snugly inside the test section. A small identifying notch was formed to mark the top centre-line of the cylinder. Cylinders were firmly secured between the access ports to prevent rotation.

The series of tests planned for the cylinders is similar to that of the flat plates, covering a range of particle size and flow conditions. To date, two experiments have been completed. The experimental parameters are set out in Table 2 below:

Table 2 - Vertical cylinder experiment parameters

Test	Silica size	Velocity	Duration
10	125 nm	1.2 m/s	21 days
11	125 nm	2.3 m/s	14 days

The particle size was larger for the vertical cylinder tests than for any of the flat plate tests (compare Table 1 and Table 2). Another difference was the operating temperature of the rig, which was increased above 70°C in an attempt to reduce biological influences (if any). Both of these measures are considered to increase the likelihood of scaling.

The results obtained in both vertical cylinder tests were similar. The scale deposited was much harder than that seen on the flat plates and a pronounced hydrodynamic influence was immediately obvious. Most striking was that no visible scaling occurred along the stagnation line over the entire length of the cylinder. The clear area was about 3mm wide with parallel rows of “picket fence” scaling either side of the stagnation line. Scale in these “fences” appears to lean toward the stagnation line (ie into the flow) when examined under a microscope. Hard scale formed rows perpendicular to the flow direction from the edge of the stagnation line to a point about 90” around the cylinder on each side. The back half of the cylinder appeared to be essentially free of scale.

The scales deposited on the cylinders are much more like those commonly seen in geothermal fields than the scales deposited on the flat plates. Higher temperatures were used in the cylinder tests, which are also zinc free. This leads us to believe that the vertical cylinder tests do not have the biological influence seen in on the flat plates but, as yet, this remains unconfirmed.

Compared to the cylinder results described by Garibaldi (1980) there are some similarities and some differences. Garibaldi described needle-like structures in areas of well-directed flow; we describe a similar “picket fence” structure in the same regions (ie. the upstream sections). However, Garibaldi observed high scaling rates at the stagnation line, where we saw a complete absence of scale. In addition, the early work described a cellular structure in the zone of recirculation, while we did not observe scaling in the recirculating zone (on the back of the cylinder). On our samples it appears that the open areas between the “picket fence” rows had begun to fill in and, had our samples been exposed for longer, we may have seen results more similar to those of Garibaldi (ie. the development of the cellular structure). Further tests are required to confirm this.

FUTURE **WORK**

It should be emphasised that these experiments are preliminary, and there have been major outages of the plant. As well, we are still learning how to reproduce silica colloids of a particular size.

At this time it is suspected that the presence of bacteria has had a major influence on the results of at least some of the experiments. The source of these bacteria has not been investigated. Although the bacteria can be air transported, it is possible that a plywood divider used in the pre-treatment hold up tank is contaminating the fluid.

Since the thermophilic bacteria can live at temperatures up to – 130°C, the result; do have consequences for scaling in geothermal power plant. In cooperation with NASA, we hope to characterise the bacteria, and try to characterise the nutrients that are required for their growth.

Since it appears that the zinc is necessary for growth of the bacteria, we intend to conduct a series of experiments using experimental plates from which all of the zinc coating has been chemically removed. From the results to hand, it appears that mechanical removal by bead blasting does not completely remove all of the zinc. The only tests which have so far produced the hard scale we initially expected are the vertical cylinders. These cylinders are zinc free.

The deposited scale from all of the experiments conducted so far will be investigated by SEM, HR-TEM and chemical analysis. Using these techniques, we hope to establish the micro-morphology of the deposit and characterise chemical elements that are co-precipitated with the silica. The latter may lead to information about the required nutrients for growth of the bacteria.

Following these experiments, we hope to be able to sterilise the complete system in order to investigate scaling in the absence of the thermophilic bacteria. These future experiments will then be relevant to those geothermal situations above temperatures of –130°C.

Continuing development of the silica colloid preparation stage of the plant is also required in order to better control the particle size of the colloids that are formed.

CONCLUSIONS

These experiments are only in the preliminary stages, however, the principal conclusions of the experiment so far, is that there seems to be some microbial mediation of silica scaling in the system that we have constructed. A further conclusion is that zinc seems to be an essential nutrient for the growth of the bacteria. To date, an identifiable hydrodynamic influence has been observed only in the last two tests, both on vertical cylinders.

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