SILICA SCALING UNDER CONTROLLED HYDRODYNAMIC CONDITIONS.

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Abstract

Silica scaling on the surface of a flat plate 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 jlow characteristics, silica colloid particle size and the scaling process, and to thereby understand the fundamental processes involved in silica scaling in geothermal systems.

1.0 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, 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.

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 emphasised the polymerisation kinetics of silica, and the effects of pH, other ions I

n 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 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 with their axes perpendicular to the flow 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.

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 last year (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.

2.0 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. 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.

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.

3.0 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 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, of which only a very small percentage actually precipitates, but is to ensure that any trace components which 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.

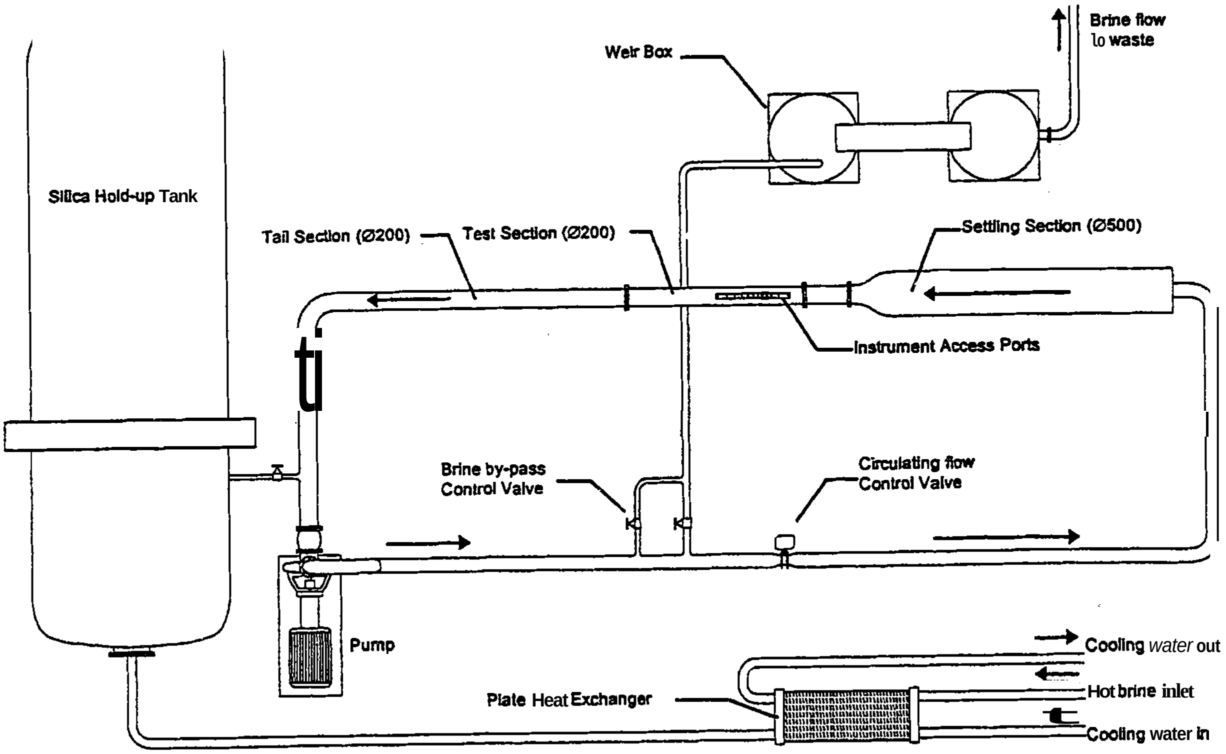

Figure 1 Recirculating test rig

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 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 for 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 in this example range from 15nm to 70nm, but the distribution is monodisperse with an average size of 23nm.

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 differential 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.

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 3.

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.

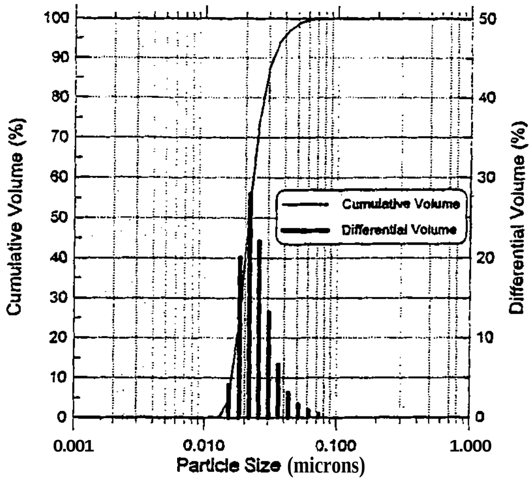

Figure 2 Colloid size analysis

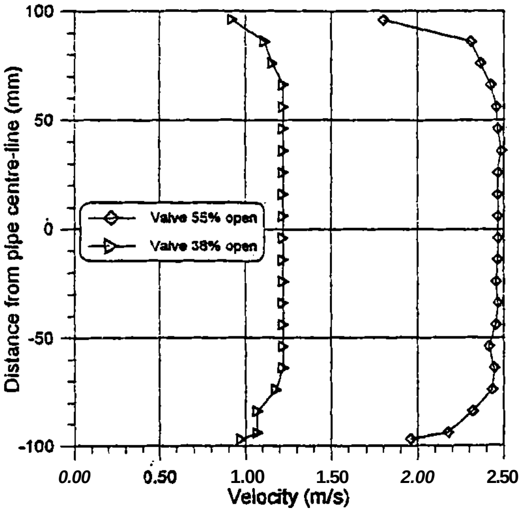

Figure 3 Velocity profile in the test section

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.

A series of tests were 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	1.2m/s	31 days
4	29 nm	1.2 m/s	17 days
5	34 nm	2.0m/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 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. In test 9 there is the possibility of a discernible zone of decreased scaling on the leading edge of both sides of the plate. This zone is approximately **1.5** cms 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.

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 scale 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 test there was no observable influence of hydrodynamics in the scaling process.

In experiment #8, the plate was covered with a yellow deposit. **This** is assumed to be sulphur which was formed 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 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. Following examination by collaborative scientists **from** the exobiology unit at NASA, it was proposed that the scale that was 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 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 Figure **4.** The mild steel cylinders were **25mm** in diameter, and sized to fit exactly across the whole diameter of the test section. The planned experiments are similar to those of the flat plates. To date, two experiments have been completed. For both tests **(#10** and #11), the colloidal silica particle size is 125 nm. The velocity was **1.2 m/s** for test **#10** which ran for **21** days, and the velocity was **2.3 m/s** for test **#11** which ran for **14** days.

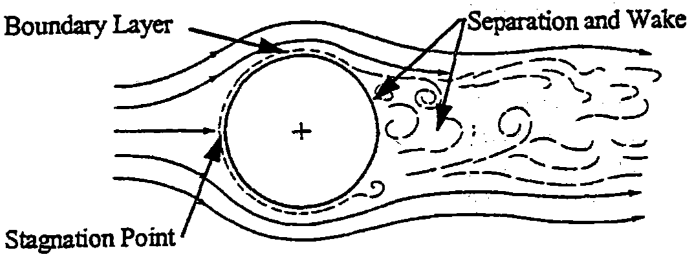

Figure 4 Flow over a cylinder (White, 1979)

The particle sizes are larger for these experiments, and the operating temperature was raised above ~70°C, in order to try to reduce any biological influence. Both of these measures would be expected to increase the likelihood of silica scaling.

The results obtained in the two cylinder experiments to hand are similar. The scale deposited was much harder than that observed for the flat plates, and a hydrodynamic influence was immediately obvious. Most striking was that no visible scaling occurs along the .{hole length of the stagnation line. This clear area was about 3mm wide. On either side there was an area of “picket fence” silica scaling, with the “fences” being parallel to the length of the cylinder and pointing into the flow. This type of scaling was evident from the edge of the stagnation line, to a point about 90” around the cylinder from the forward facing side. The back half of the cylinder, whch was facing away from the flow direction 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 observed on the flat plates. Higher temperatures were used in these experiments, and the samples were zinc free. We believe, therefore, that the vertical cylinder tests do not have the biological influence seen on the flat plates, but as yet, this remains unconfirmed.

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° 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.

5.0 FUTURE WORK

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

At this time 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 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 results 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 those of the vertical cylinders which 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.

6. 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, at higher temperature and with no zinc present.

7. ACKNOWLEDGMENTS

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