CFD MODELLING OF CORROSION TEST LOOPS FOR GEOTHERMAL FLUID APPLICATIONS

Keith Lichti[1], Rosalind Julian[1], Cole Davies[1], Bruno Fletcher[2], Kazumi Osato[3], Masatake Sato[3], Kaichiro Kasai[3], Norio Yanagisawa[4], Koji Sakura[5]

[1]Quest Integrity NZL Limited, PO Box 38096, Lower Hutt, New Zealand

[2]Gulfstream Aerospace, 500 Gulfstream Road, Savannah, GA 31408, USA

[3]Geothermal Energy Research & Development Co., Ltd. (GERD), Shinkawa-1 Chome, Chuo-ku, Tokyo 104-0033, Japan

[4]Renewable Energy Research Center, AIST, 2-2-9, Machiikedai, Koriyama, Fukushima 963-0298, Japan

[5]TenarisNKKTubes, 1-10, Minamiwatarida, Kawasaki, Kanagawa, 210-0855, Japan

K.Licjti@QuestIntegrity.com

Keywords: *geothermal, corrosion, scaling, monitoring, test loop, CFD, field testing*

ABSTRACT

Small bore corrosion test loops in side streams have been commonly used for many years in the oil and gas industry for cooling water corrosion monitoring. This work describes a high temperature flowing brine test loop for on-line Electrical Resistance, Linear Polarisation Resistance and ASTM coupon exposure testing in geothermal applications. CFD modelling of the Electrical Resistance probe access points is presented for small bore piping in “T” and “Y” configurations that achieve mass flow rates similar to pipeline conditions while minimizing the effects of the test element finger intrusion into the flowing brine stream.

1. INTRODUCTION

Facilities for field testing of geothermal fluids are required for many applications where the geothermal steam and brine chemistry presents a significant variation to historical work making testing a requirement prior to materials and process selection. Large teams of engineers, geochemists and technicians are required for full size applications that use dedicated purpose built equipment to replicate production equipment. The cost of these has become prohibitive from many aspects including materials costs but more importantly manpower for design, fabrication, transport, installation and operation, Lichti et al. (2010).

GERD with the support of Quest Integrity have completed a number of field tests using a side stream corrosion test loop. The testing has been completed in brine and two-phase fluids using a loop design based on lower temperature test facilities commonly used in recirculating cooling water applications, see for example Richter and Thorarinsdottir (2013). The cooling water applications typically use rod coupons exposed in a “T” arrangement with the monitor inserted through the T and flow along the monitor and downwards. The use of on-line corrosion monitors allows the testing to be completed in a short period of time but the loops can be used for extended period testing as well.

An advantage of small bore geothermal fluid side stream test loops is that the amount of fluid passing an inserted monitor can be controlled to mimic the flow past a full size casing, pipe wall or heat exchanger tube wall under controlled test conditions without the complications from operation of and access to full size plant. Simple flow velocity calculations for smaller bore corrosion test loop piping can be done. The aim of this work was to improve the ability to relate corrosion monitoring results to actual plant conditions.

This paper compares fluid flow patterns and wall shear stress of two variations of the corrosion test loops of the type used previously by Quest Integrity as illustrated in Figure 1a and an optimization made by GERD. The comparisons are made with the aid of Computational Fluid Dynamics (CFD) using pressurized flowing single phase liquid (water described by IAPWS-IF97(2007) model) at saturation temperature. A novel feature of the GERD testing has been in the use of the developed corrosion test loop for two-phase fluids with the loop oriented vertically. This variation has not been modelled but will be briefly discussed.

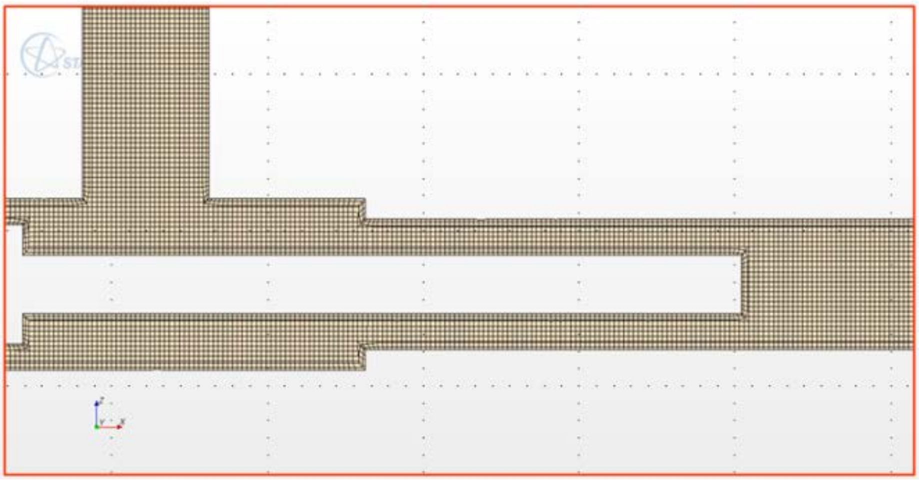
2. CORROSION TEST LOOP - APPLICATION OF CFD

The first attempt by Quest Integrity to model a small bore side stream test loop was completed for ¾ inch pipe geometry. A short length of ¾ inch pipe was presumed to provide laminar fluid flow up to the test “T”, also in ¾ inch. A single phase mass flow rate at brine saturation temperature was presumed for the pipe with higher and lower flow rates also able to be considered. An 8.0 mm rod sample down the center of the pipe having nominal diameter of 19 mm was presumed for modelling purposes. The pipe orientation presumed for the modelling was horizontal. The CFD code used was STAR-CCM+ [1]. An unstructured hexahedral trimmed mesh type was used for the CFD modelling with ~ 461,000 cells as shown in Figure 1b. The model was developed for a horizontal arrangement and gravitational effects were included.

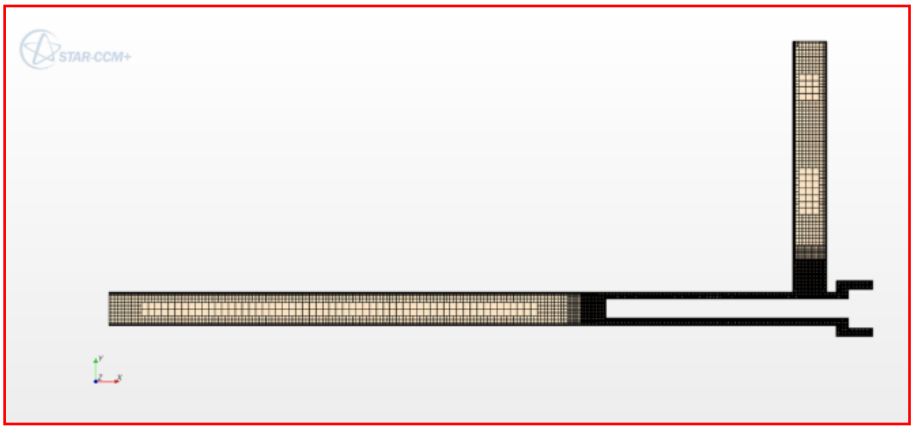
The second application was made for a smaller bore pipe, nominal internal diameter 13.8 mm, with the same 8.0 mm rod sample down the middle of the T and into the pipe. The model for this condition was similar to that for the larger diameter and completed for a horizontal arrangement with gravitational effects included. The mesh was changed for the smaller diameter and a trimmed polyhedral mesh containing approximately 630,000 cells with prism cells along the wall to model turbulence. The mesh for the small bore pipe is illustrated in Figure 1c.

The GERD optimization used an increased internal pipe diameter of 1”, nominal 25.4 mm, with the same 8.0 mm rod sample down the center with a tangential exit from a fabricated Y, see Section 2.3 below. This optimization was also later used for two-phase fluid with a vertical orientation and an upward flow in the fluid supply to the Y. The two-phase application has not been modelled as part of this work.

a) Typical ¾ inch test T and ER probe arrangement.



b) ¾ inch pipe and T mesh.



c) Small bore (13.8 mm internal diameter) pipe and T mesh (top view).

Figure 1: Mesh geometries used for CFD modelling of the ER probe in the T arrangements.

2.1 ¾ Inch T Arrangement

The results from this model are summarized in Figure 2 for a mid-range mass flow of 6600 kg/hour. The figure shows the pressure distribution, wall shear stress and fluid velocity contours for this condition. Flashing and cavitation are not modeled; rather the possibility of either happening is based on the pressure drop encountered across the assembly. If the pressure drops below the saturation pressure, then there is increased risk of flashing and cavitation. Flow-induced erosion was not modelled; however, the regions with high velocity will point to zones that are more prone to erosion

This ¾ inch pipe T geometry arrangement has been used to measure corrosion rates for carbon steel in a number of acidic small bore side stream test loops. Short lengths (0.5 to 4.0 m) of ¾ inch pipe were used to direct fluid taken from larger diameter flowing brine pipelines with the entry and exit for the test loops controlled by valves. The downstream fluid passing the control valves was typically flashed to a drain or silencer but also at times returned to a lower pressure part of the plant. In-line Electrical Resistance (ER) Corrosometer™ [2] probes with an 8 mm diameter test probe geometry and 100 mm length were used to monitor the corrosion rates of carbon steel in the flowing brine solutions. The test T was also used for Linear Polarisation Resistance (LPR) corrosion rate measurements with a three electrode probe with an 18 mm diameter body with electrodes of 6 mm diameter and 30 mm length. These were positioned within the main area of the T and flow conditions modelled. A comparison of the flow velocity and wall shear stress for this geometry vs the ER probe is given in Table 1.

On-site testing indicated the presence of a fluid flash and cavitation damage of the surface of the probe at the same location for all variations in chemistry and flow rate tested. This flash point was located at the exit of the T where there was a reduction in pressure resulting from the flow distribution. The objective of the on-site testing was to understand the effect of changing chemistry and was comparative (i.e. to show effects of pH variation). The evidence of corrosion of the surface suggested this flash point had negligible influence on the magnitude of the results but was still seen as a risk for interpretation of results. The test work was initiated before the CFD modelling and the CFD modelling was undertaken to determine if it was possible to predict the risk of a pressure reduction and increase in shear stress and also to improve the ability to use the corrosion results for actual plant conditions. A pressure reduction although only slight was indicated by the modelling at this location and gave a reason for the observed discontinuity feature in the appearance at that location.

In the application of the ¾ inch T corrosion test loops, at a number of different test sites, one problem that frequently arose was the presence of small stones in the flowing brine. For extended test times, these stones tended to collect in control valves and in some instances lodged beside the test probe resulting in damage to the probe on removal.

Table 1: Summary of CFD results for ¾ inch corrosion test loops with T arrangement.

Flow Rate (Corrosion Monitor)	*Maximum Velocity*	*Maximum Wall Shear Stress*	*Mean Wall Shear Stress*
kg/hr	m/sec	Pa	Pa
4010(LPR)	5	801	40
4720(ER)	6	1105	54.3
6610(ER)	8.5	2136	101
9440(ER)	12	4304	195

2.2 Small Bore (13.8 mm ID) T arrangement

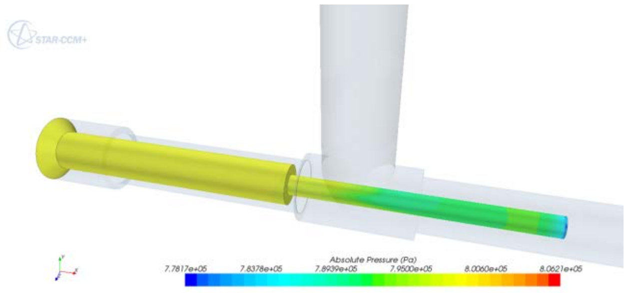
The small bore T variation was completed for a heat exchanger simulation, hence the use of a smaller diameter pipe, 13.8 mm Internal Diameter, Erstich et al. (2012). In this instance the modelled flow rate was fixed at 1000 kg/hour (first order adjustment of results for lower flows was intended to be by simple ratio application). The ER probes were fitted to a reducer and heavy wall pipe that allowed the main test element only to be inserted into the flow. The test rig was designed to simulate heat exchange for a silica saturated brine to consider the benefits of alkali pH adjustment, Lichti et al. (2020). The CFD results for this arrangement are given in Figure 3 for a horizontal layout although the implementation was with a downward facing exit of the T. Again, the CFD showed some local area pressure reduction of the brine as it passed through the in-line corrosion test loop. A feature of this facility was in the addition of a second in-line test point that allowed LPR testing to be competed in the same flowing brine stream but in this case the LPR electrode flow conditions were not modelled.

[2] TM Cosasco Corrosion Monitoring and Chemical Management Systems, USA

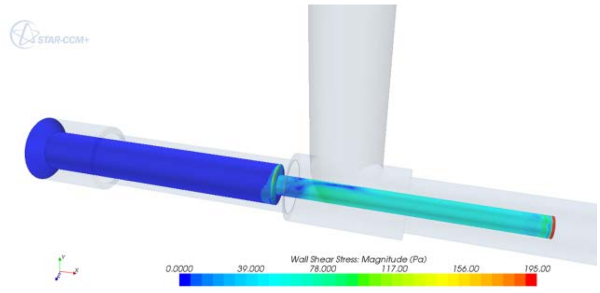
The test programme with the small bore piping was relatively short and no issues with stones were encountered.

The CFD modelling identified a number of issues with the small bore experiment design:

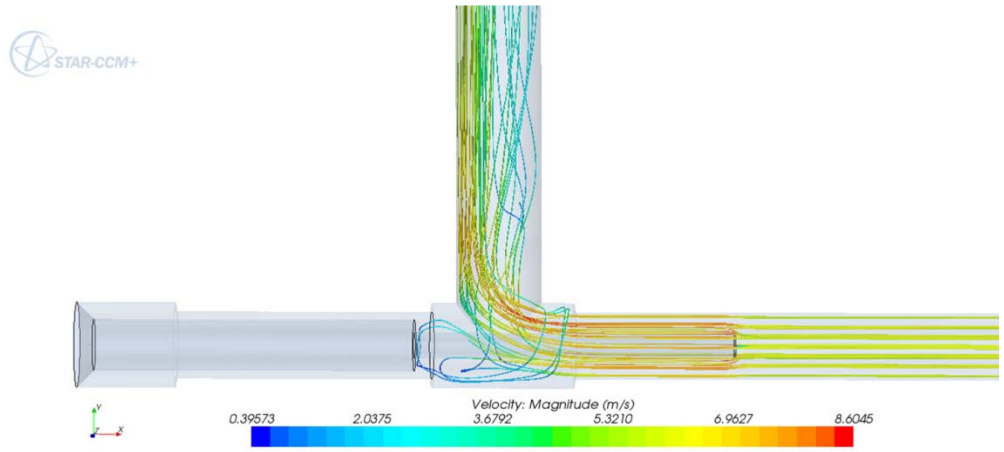
- There was a marked increase in the flow velocity along the side of the test electrode with the decrease in pipe diameter.
- The wall shear stress shows significant departure from the nominal 13.8 mm ID heat exchanger pipe material.
- The increase in pressure drop across the probe enhanced the risk of flashing on the exit – this was especially so when the entry pressure was low and the temperature decreased to less than 100 ºC.
- There was a risk of dead space at the base of the probe and this increased the risk of silica seeding of downstream test points although the downward facing exit may have reduced this risk.



a) Pressure Distribution (Isometric View)



b) Shear Stress Distribution (Isometric View)



c) Streamline Velocity (Side View)

Figure 2: Illustration of CFD results for ¾ inch corrosion test loop with T arrangement with the T being horizontal. Discontinuity feature observed at exit from T and presumed due to cavitation at low pressure location.

2.3 1 Inch Y arrangement

The GERD corrosion test loop was CFD modelled before final design. The CFD was done for the larger diameter of 1 inch selected to avoid issues with stones and provide additional flexibility in corrosion monitor insertion and removal. The same cell size as previous models was used, which meant that the polyhedral mesh contained approximately 1.6 million cells. Extruded prism cells were again used along the walls to capture the velocity gradient along the boundary layer. The Y geometry and mesh are illustrated in Figure 4a. Gravity effects were also included in this modelling.

Initial design conditions that were used for the CFD supported design were:

- Mass flow rate inlet = 8500 kg/hour.
- Pressure outlet = 1030 kPa.
- Temperature = 180 ºC.

An initial CFD model with a 1 inch entry pipe and a ¾ inch exit pipe proposed to increase the exit pipe pressure gave a high wall shear stress on the sides of the test element. Increasing the exit pipe diameter to 1 inch reduced the shear stress on the sides of the test element by 7.6 % and the final design was with a 1 inch exit pipe. The Y assemblies were manufactured by welding and machining from bar stock to reduce the internal changes in wall geometry that were encountered when using standard pipe fittings. In spite of these optimizations a stagnant area persisted at the base of the probe, opposite the exit of the Y. Figures 4b, 4c and 4d illustrate the final CFD results for the GERD Y corrosion test loop.

The GERD Y design corrosion test loop was used at two geothermal power station sites on two separate occasions for each. (Yanagisawa et al. 2015; Osato et al. 2015) Four Ys were used in sequence for the test loops as illustrated in Figure 5 with the test points used as follows:

- The first Y was dedicated to ER probes of the type modelled by CFD.
- The second Y was used for LPR probes with a side port for a Ag_2S reference electrode.
- The third Y was used for cylindrical in-line coupons of a similar diameter to the ER probe. This port was also used in some tests for a second ER probe or for individual rod coupon exposures.
- The fourth Y was used for an in-line thermocouple pocket.

Brine mass flow rates from 450 to 600 kg/hour were used for brine tests. These flow rates were much less than the modelled mass flow because of limitations in the available fluid and at these lower flow rates the GERD Y design showed no discontinuities in the surface condition of the exposed ER test elements indicating very low risk of flashing and cavitation. Figure 6a illustrates carbon steel ER accumulated material loss results for a pH 3.6 brine environment at 120 ºC, obtained using the GERD Y design corrosion test loop as described by Osato et al. (2015).

A two-phase experimental test programme was completed using the GERD Y design corrosion test loop oriented vertically, Yanagisawa et al. (2015). The total mass flow rate was 360 kg/hr. Brine to steam ratio was estimated from well flow measurements to give a calculated flow velocity of 1.9 m/s. Example ER probe results for the two-phase fluid at pH 4.0 and 165 ºC are illustrated in Figure 6b. This vertical arrangement for the two-phase fluid test had several advantages:

- The ER probe at the first Y was exposed to rising fluid intended to simulate two-phase fluid rising in a geothermal well.
- The LPR at the second Y was in a well of brine and the nearby Ag_2S reference electrode performed well in the wetness present.
- The coupons at the third Y were again in the two-phase rising fluid.

3. SUMMARY AND CONCLUSIONS

The development of a corrosion test loop arrangement for geothermal energy materials testing applications has been progressed from simple assembled ¾ inch T arrangements to small bore, 13.8 mm ID pipe and T followed by a 1 inch fabricated Y. All of the used corrosion test loops provided opportunity for on-line corrosion monitoring using ER and LPR probes and in-line coupons. Ag_2S reference electrodes were readily incorporated in all of the designs. CFD analysis of the test arrangements demonstrated that the latest development, the Y design, provided advantages for brine applications with respect to decreased risk of pressure drop leading to flashing around the corrosion monitors and a decreased risk of small stones collecting around the monitors. The Y design has also provided opportunity for testing of two-phase fluid using a vertically oriented test loop – the two-phase geometry was not CFD modelled in this work but an estimated fluid velocity of 1.9 m/s was indicated.

None of the corrosion monitor access points were free from risk of stagnant areas that may act as seed points for silica precipitation and onset of downstream scaling that would not occur in the absence of the in-line test point. The Y design did show some reduction of this risk. The first access point in each loop would of course have minimal risk of silica seeding making it an ideal test for risk of scaling when used for long term testing provided the risk of flashing was low.

ACKNOWLEDGEMENTS

The GERD research project is supported by New Energy and Industrial Technology Development Organization (NEDO). The authors express their thanks to Quest Integrity for permission to publish the CFD work.

REFERENCES

Erstich, E., Mejorada, A., Lichti, K. and Brown, K.: Binary Plant Caustic Dosing Test Rig Development, New Zealand Geothermal Workshop Proceedings 19 - 21 November Auckland, New Zealand, (2012),

Lichti, K.A., White, S.P., Ko, M., Villa, Jr. R..R, Siega, F.L., Olivar, M.M.M., Salonga, N.D., Ogena, M.S., Garcia, S.E., Bunning, B.C., Sanada, N.: Acid Well Utilisation Study: Well MG-9D, Philippines, World Geothermal Congress, Bali, Indonesia, April, (2010),

Lichti, K., Julian, R., Brown, K., Villafuerte, G., and Dambe, R.: Scaling and Corrosion Control in a High Chloride Geothermal Brine, in Proceedings World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2. (2020).

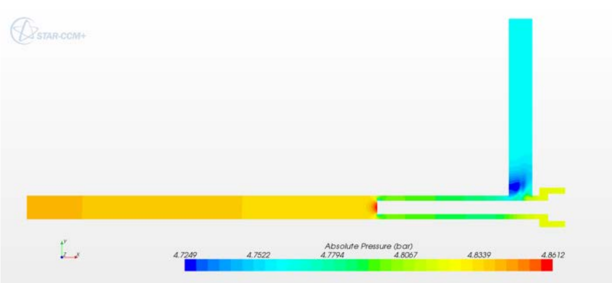
Osato, K., Sato, M., Kasai, K., Omae, M., Yanagisawa, N., Sakura, K., and Lichti K.: Development of New Field Testing Tools for Geothermal Power Plant Risk Assessment of Corrosion and Scaling, in Proceedings 39th New Zealand Geothermal Workshop, 22 - 24 November, Rotorua, New Zealand. (2017).

Richter, S., and Thorarinsdottir, R.I.: Factors Affecting Corrosion in Low Conductivity Geothermal Water, NACE Corrosion/2013, Paper No 2465. (2013).

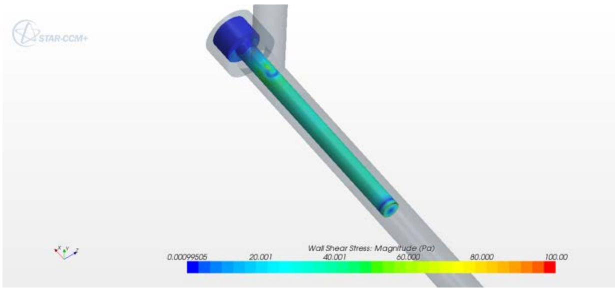
Yanagisawa, N., Masuda, Y, Osato, K., Sato, M., Kasai, K., Sakura, K., Fukui, T, Akahori, M., and Lichti, K.: The Material Corrosion Test Using Loop System Under Acidic Condition at Geothermal Field in Japan, in Proceedings 39th New Zealand Geothermal Workshop, 22 - 24 November, Rotorua, New Zealand. (2017).

IAPWS-IF97 (2007) The International Association for the Properties of Water and Steam, Lucerne, Switzerland, August, Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam. (2007).

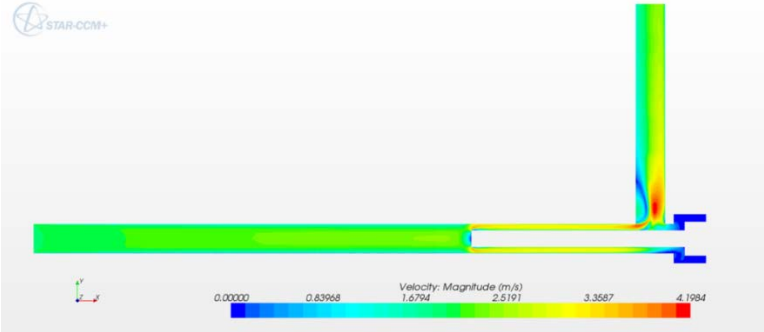
a) Small Bore Corrosion Test Loop ER Probe Access Point. (Note the discharge was implemented in a downwards orientation and the exit flow severely throttled by the control valve rather than the horizontal condition and longer exit pipe modelled.)



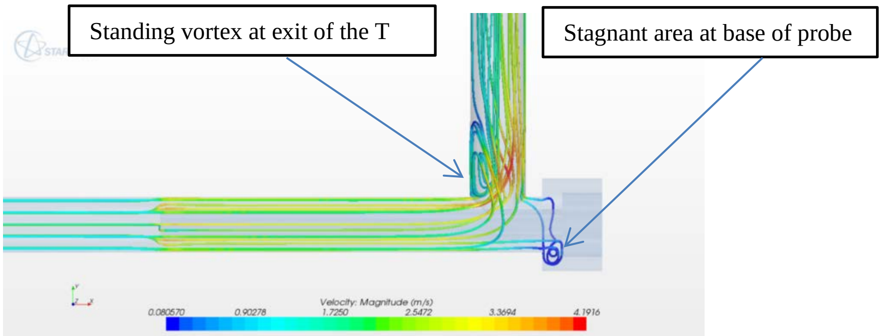
b) Pressure Distribution (side View)



c) Wall Shear Stress (Isometric View)

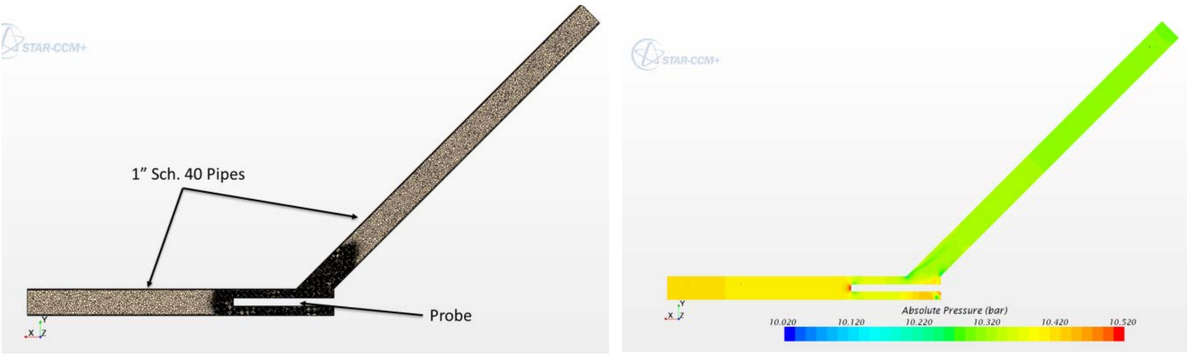


d) Velocity Distribution (Central Plane View)

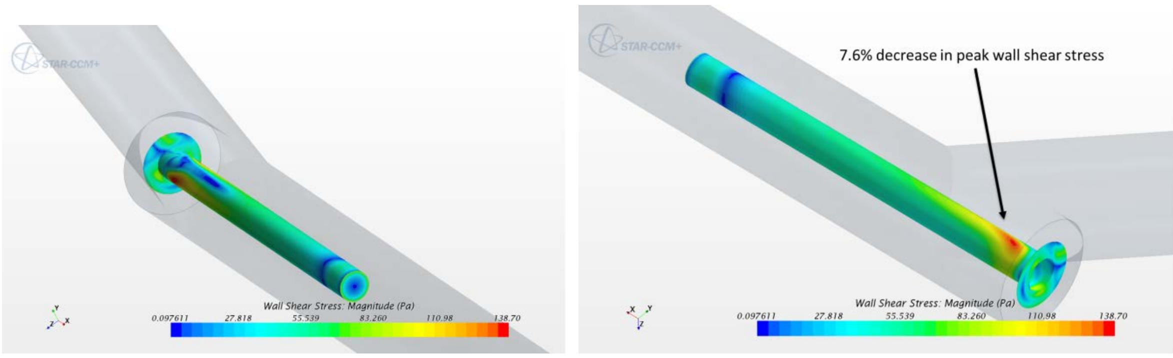


e) Velocity Profiles (Streamline View)

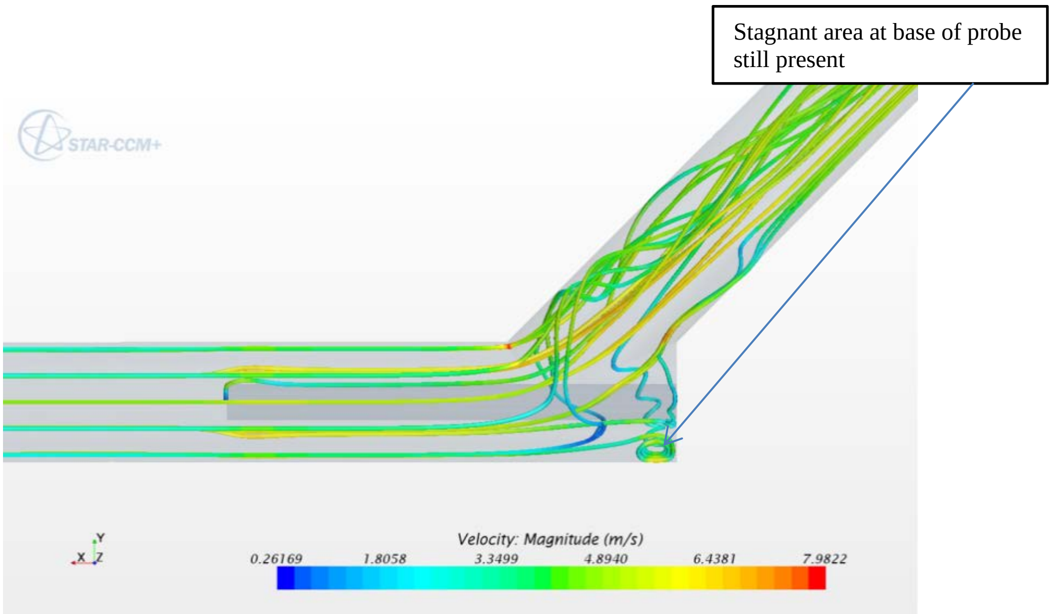
Figure 3: Illustration of CFD results for small bore (13.8 mm ID) corrosion test loop with T arrangement.



a) Mesh used for GERD corrosion test loop Y design   b) Pressure Distribution (side View)



c) Wall Shear Stress (Isometric Views)

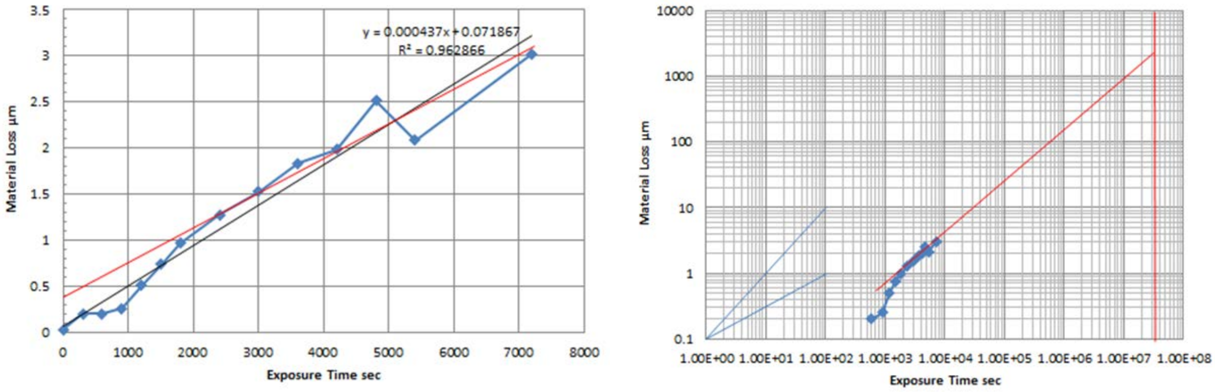


d) Velocity Profiles (Streamline View)

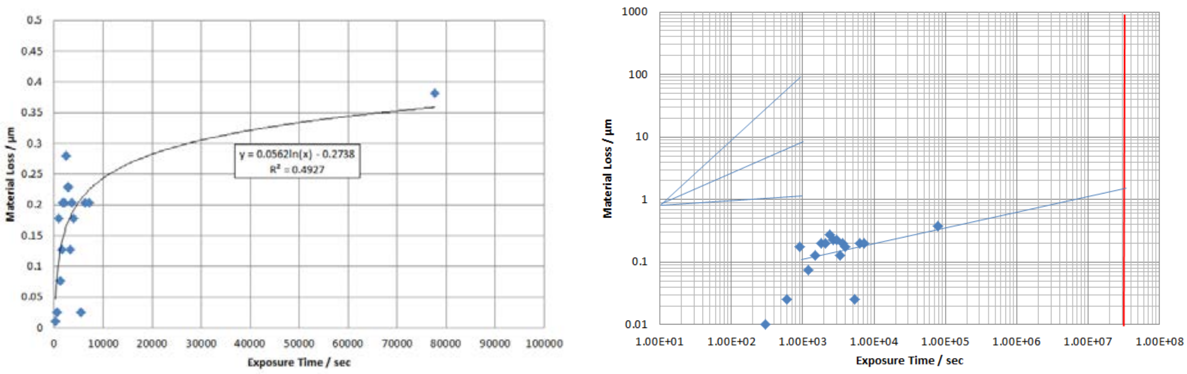
Figure 4: Illustration of CFD results for GERD corrosion test loop with Y arrangement.

•


- **Figure 5: Illustration of GERD corrosion test loop with Y arrangement being used for acidic brine testing, Osato et. al. (2016).**



a) Carbon Steel ER Probe Material Loss Results for Brine at pH 3.6 with a Mass Flow of 620 kg/hr at 120 ºC.



b) Carbon Steel ER Probe Material Loss Results for Two-Phase Fluid at pH 4.0 and a Flow Velocity of 1.9 m/s at 165 ºC.

Figure 6: Illustration of brine and two-phase corrosion test results for the GERD corrosion test loop with Y arrangement.