

Pilot Rig Scale Testing: Hydrodynamics and Scale Deposition

Neil Goodwin, Mark May, Amarpreet Kaur, & Gordon M. Graham
Scaled Solutions Ltd
6 Nettlehill Road, Houstoun Ind. Est.
Livingston, EH54 5DL
UK

ABSTRACT

Hydrodynamic factors, such as shear stress and turbulence, are known to affect scale deposition and corrosion in oilfield production systems. Systems in which the configuration promotes sudden changes in the degree of turbulence can be particularly susceptible to scale deposition problems, as is often observed in chokes, pumps, valves and (most relevant here) in the vicinity of inflow controls devices (ICDs).

This paper documents the development of pilot rig testing methodology, which aims to achieve far more field-realistic flow regimes than typically obtained in laboratory tests, and applies it to the study of scaling phenomena in and around ICDs, using up to 8000 liters (L) of scaling brine flowing through the system on a single-pass basis at a fluid flow of 10 L/min. Custom designed and manufactured test pieces were incorporated into the rig to determine the extent and location of scale deposition as a function of varying wall shear stress. Interpretation of the observations was enhanced through the use of computational fluid dynamics (CFD) to quantify and assess the contribution of various hydrodynamic factors on scale deposition.

The work therefore demonstrates the effectiveness of pilot-rig test methodologies for use in oilfield applications where the influence of the hydrodynamic regime is likely to be significant. Moreover, by showing how the scaling results correlate with CFD predictions, it increases the confidence that design decisions based upon laboratory tests will be valid under field conditions.

Key words: Scale Deposition, Turbulence, CFD, Pilot, Hydrodynamics

INTRODUCTION

Limitations of Current Scale Prediction Models

The vast majority of scale prediction models are based on thermodynamic calculations. They may be used to predict the Saturation Ratio (SR, the thermodynamic driving force for precipitation) and the Excess Solute (the maximum mass of scale that can precipitate per unit volume of brine if the system were to reach equilibrium) for a particular system, but thermodynamic models do not take kinetic factors

into account and cannot predict the rate of scale formation. Kinetic factors are particularly important in mildly supersaturated systems, as has been reported in numerous publications.¹⁻¹¹ Kinetic factors mean that some mildly supersaturated systems do not significantly precipitate within production timescales but remain metastable. A simplified illustration of this is shown in Figure 1 for calcium carbonate (CaCO_3), showing that various stability regimes can be defined as a function of temperature. Saturation Ratio is defined such its value is unity at equilibrium; $\text{SR} < 1$ represents an under-saturated system; $\text{SR} > 1$ represents a supersaturated system, which may precipitate to some extent if kinetic factors are favourable.

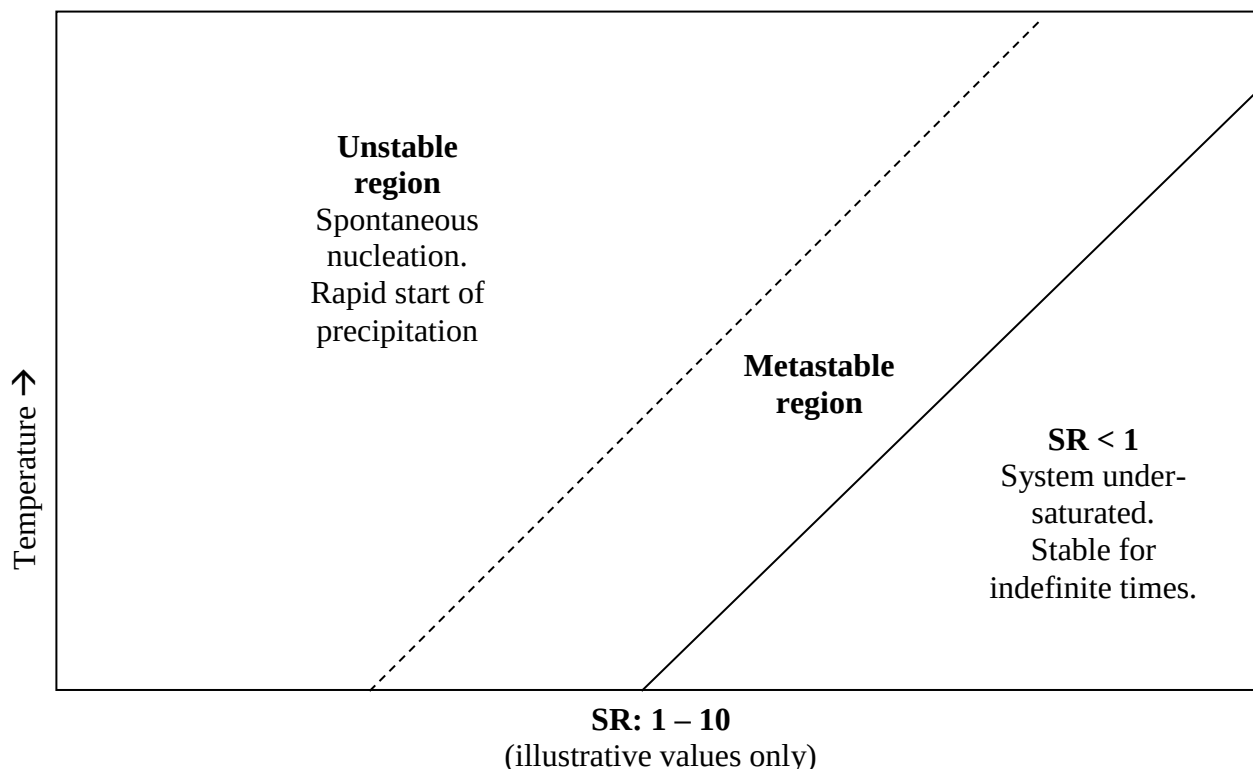


Figure 1: Simplified illustration of stability zones for CaCO_3 precipitation showing the influence of temperature (pressure and other factors also have an effect).

As there are recognized gaps in the current knowledge, a number of research groups have looked at methods that will allow investigation into the non-thermodynamic factors that influence scale precipitation and deposition. Many of these have focused on the impact of fluid dynamics on mildly oversaturated systems.

Laboratory Investigations into the Effect of Hydrodynamics on Scale Deposition

Conventional laboratory techniques used in the oil and gas industry for assessing the likelihood of inorganic scale formation include bulk “static” bottle tests and dynamic “tube-blocking” tests. These methods are useful as they are relatively quick and easy to carry out but have well-known limitations, which have been previously reviewed and discussed in detail.^{1,2,12} An important limitation dynamic tube-blocking is that the flow is laminar, which is not representative of the turbulent flow typically present in a production system. Moreover, the residence times in the tube are very short, which means that without “pre-scaling” the tube, the test is disproportionally influenced by nucleation phenomena rather than crystal growth. It is very common that scaling tendencies that may lead to operationally significant deposition in the field show no indications of this in such tests, making it necessary to increase the concentration of scaling ions in the laboratory to achieve a “blank”, uninhibited scaling rate that is practicable for testing of scale-inhibitor performance but no longer representative of the field condition. An alternative is to

include a filter downstream of the scaling tube to measure precipitation, though, of course, the test no longer becomes a measure of the degree of deposition (it can sometimes even lead to the precipitation of the wrong mineral!). In bulk “static” bottle tests, mildly supersaturated brines can also remain metastable for greater than typical test times of 2 – 48 hours. Therefore, modified techniques, such as stirring or “seeding” (adding small crystals of the scale mineral), are necessary to achieve sufficient precipitation to assess the efficiency of chemical inhibitors.

Reynolds number (Re) is a dimensionless number used to characterize fluid behavior and is commonly used to determine the transition between laminar and turbulent flow. Reynolds number is defined as follows:

$$Re = \frac{\rho u D}{\mu}$$

Where; ρ is the fluid density (kg/m³)
 u is the fluid velocity (m/s)
 D is the internal pipe diameter (m)
 μ is the dynamic viscosity (kg.m⁻¹.s⁻¹)

Laminar flow occurs when a fluid flows in an ordered fashion; essentially all elements of the fluid move parallel to the overall flow vector, with no lateral mixing or cross currents. A Reynolds number of less than 2,100 is typical for laminar flow in a pipe. Turbulent flow in a pipe occurs at higher Reynolds numbers, typically above 4,000, and is characterized by chaotic changes in flow velocity (speed and direction). Between these values is a flow regime described as transition flow.

Flow in a typical laboratory tube blocking test is characterized by Reynolds number of less than 1,000, and, as stated above, is not representative of field conditions. A comparison of typical wall shear stress and Reynolds number values for a dynamic tube-blocking test and field pipe flow conditions is presented in Table 1.

Table 1
Shear Stress and Reynolds Numbers for Laboratory Tests Compared with the Field

Condition	Flow Rate	Internal Diameter	Reynolds Number (Re)	Wall Shear Stress (Pa)
Dynamic test	10 ml/min	1 mm	350	1.05
Dynamic test	50 ml/min	1 mm	1,750	5.25
Pipe flow in field	1,000 m ³ /day	5 inch	191,715	1.91
Pipe flow in field	1,000 m ³ /day	4 inch	238,281	4.65
Pipe flow restriction	1,000 m ³ /day	2 inch	479,080	82

With regard to the investigation of scaling in and around ICVs and ICDs, the standard methods and equipment are not capable of achieving high shear, turbulent flow conditions generated by these devices. In addition, none of them provides information on the location of scale relative to system configuration, which may be an extremely important factor in and around ICD nozzles, within chokes, in and around a safety valve, etc.

Despite growing recognition of these issues, there remains only limited investigation in the literature regarding the development of test methodologies for the assessment of scale formation under high shear, turbulent flow conditions and in configurations that are representative of real, scale-susceptible components in the field. Most of these test methods focus on comparing laminar and turbulent flow regimes, and provide good evidence for the increased risk of scale formation under turbulent flow, but

the reported techniques do not achieve typically the very high shear stresses experienced in certain field situations, such as inflow-control components.

Quddus *et al.* conducted an investigation into BaSO₄ scale deposition on stainless steel surfaces using a rotating cylinder method.¹³ With increasing rotation speed (1000 to 3000 rpm, corresponding to Reynolds number 14,000 to 44,000), weight gain on the steel surface was found to increase, providing evidence for increased scale deposition under more turbulent conditions. However, these Reynolds numbers remain significantly lower than those typical of flow in a simple pipe (Table 1), let alone those that could potentially be reached in ICDs, which could be up to 700,000. In contrast, Graham *et al.* found that while turbulent flow resulted in increased bulk precipitation in a stirred system, adhesion of scale to a metal surface was lower under the investigated turbulent flow conditions than under laminar flow.¹⁰

An alternative test method employed by Benvie *et al.* consisted of the introduction of an adjustable small-bore valve into the middle of the scaling coil in a dynamic tube blocking rig to restrict the diameter and increase the shear stress.¹⁴ The most significant impact on the uninhibited scaling time was seen when the valve was introduced in the center of the scaling coil. However, the valve in these tests was fully open and the magnitude of the restriction is not indicated, nor was the shear stress quantified.

Another example of a dynamic flow rig used for assessment of scale under turbulent flow conditions was reported by Jøsang *et al.*¹⁵ A purpose-built ‘turbulence rig’ was used to assess the influence of an expansion in tubing diameter on CaCO₃ scale deposition. As flow rate was increased, scale growth rate also increase in the region directly after the expansion, where backwards flowing currents and eddies are expected. Due to the constraints of operating on a laboratory scale rig, this equipment was not capable of achieving the highest shear forces that may be experienced in the field. The primary reason for this was the large quantity of fluid that would be required to operate the rig under continuous flow with brine replenished throughout an experiment.

Related studies investigating the effect of turbulence on barium sulfate and strontium sulfate scaling in standard bottle tests have also been described.^{16,17} Turbulence was generated by stirring or gas sparging. The highest Reynolds numbers in these tests were calculated to be 8,000. It was found that more BaSO₄ scale was formed under turbulent conditions than in static tests, but for SrSO₄ the quantities were similar in each test. For both scales, scanning electron microscopy (SEM) analysis showed smaller particles were formed with increasing turbulence, suggesting increased nucleation. Higher concentrations of inhibitors were determined to be required under turbulent conditions. Chen *et al.* reported the use of rotating cylinder testing to examine the performance of different inhibitor chemistries against BaSO₄ scale.¹⁸

The effect of shear on calcium carbonate scaling has been reported from works conducted by Graham *et al.* into the adhesion and location of scale in ICVs and the effect of different metallurgies and surface coatings.¹ Tests were carried out using a rotating cage autoclave apparatus that allowed the scale deposited on metal coupons to be investigated at different wall shear stress (up to 63 Pa), but also under field-representative temperatures and pressures. It was found that with a mildly scaling brine, increasing the shear stress resulted in more scale deposition. However, with a higher SR and higher salinity brine, the mass of deposit was seen to increase initially as the shear increased, but then decreased as the shear was increased further. It was proposed that this may be due to shear at the higher values tested promoting homogeneous precipitation of scale in the bulk, which competes with surface deposition by relieving the supersaturation *via* an alternative path.

Jet impingement (JI) testing is a well-established method for examining corrosion processes under high shear flow conditions.^{19,20} It involves a high velocity jet of fluid from a small-bore nozzle which is directed at a flat metal coupon held perpendicular to the jet. Shear stress varies across the coupon surface as the fluid flows radially out, but this can be readily calculated, and it means that this system often reproduces (at least qualitatively) aspects of what happens in the field, *i.e.*, where the shear rate can spike up upon flowing through a specific component, and then rapidly reduce again to “pipe flow” levels.

The method also enables deposition to be directed onto a specific surface, which facilitates comparing deposition onto different coupon materials, different surface finish, influence of surface corrosion, *etc.* The shear stress generated can be easily controlled by altering the nozzle diameter and flow rate. It is possible to achieve very high shear stresses, representative of those expected in the field, which the other techniques described above are unable to reach. We have developed new test methods for scale formation using jet impingement over a wide range of shear stresses.²¹ These methods are now routinely used for experimental works (including scale inhibitor performance studies under very mild conditions).

All the laboratory techniques suffer limitations with regard to *some* aspect of the hydrodynamics on scale deposition in the field:

- Stirred / rotational tests fail to recreate the flow regime within pipeline flowing systems
- Jet impingement has variation in shear stresses which reach a maximum in the nozzle and on the surface, but also include low shear areas within the same test. In addition, the surface area available on the test coupon is low compared with the bulk fluid, meaning that it only recreates a small part of the field fluid dynamics and in many cases bulk scaling can predominate as a result of the increased turbulence near the coupon surface
- Most laboratory tests use a single aqueous phase and cleaned surfaces
- Flow systems generally fail to reach the very high shear stresses seen in some field devices and have a combination of short residence times and limited volumes

In addition, the majority of the reported techniques rely on simple calculations of the fluid dynamics which do not lend themselves to scale up to full field systems. This is an area that requires the application of Computational Fluid Dynamics (CFD) to allow comparison between the bench top and full-size systems.

Computational Fluid Dynamics (CFD)

CFD is a highly effective means of visualizing the flow field through a system and of calculating key parameters such as pressure, velocity, wall shear stress, density, *etc.* at various locations within the system. The combination of data and illustrative images produced by CFD may be utilized as part of the test design process, *e.g.*, to determine where in the system a particular parameter is maximal or minimal and the consequences this may have for the system. CFD can then be used to compare fluid behaviour within the laboratory tests and the field equipment.

Large Scale Flow Loops – “Pilot Rig”

Large scale flow loops or “pilot” rigs are used to bridge the gap between benchtop laboratory tests and full scale field trials. They allow full control of the test conditions (temperature, pressure, pH, flow regime and internal surfaces) and allow detailed observations to be made and validated. In addition to conducting full / large scale tests, they can be used to validate smaller scale (and less expensive) laboratory tests.

The high flow rate, pilot-scale test methodology was originally developed to examine calcium carbonate (CaCO_3) deposition in inflow control valves (ICVs).^{1,22} For these tests, 2,000 L of brine was preheated to 75 °C and pumped at 8.5 L/minute and 208 bar through an ersatz ICV having the general geometrical features of a typical field valve. Supersaturation of CaCO_3 was achieved by continuous injection of a sodium bicarbonate stock into the main flow stream. This work looked at the effects of shear stress (0.1 to 80 Pa) and of scale-resistant coatings upon the mass of scale deposited onto various surface types.

More recently, pilot-scale tests have been conducted at 10,000 Pa, to mimic the most extreme conditions expected in oilfield applications. Unlike jet impingement tests, pilot rig tests allow for fluid flow through a pipe, and so can produce a constant wall shear stress along the length of a test piece. In addition, mimicking the effects of concentric restrictions, bends or side ports is also possible with the test piece.