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CHARACTERIZATION OF THE ROUGHNESS PATTERN AND REYNOLDS NUMBER EFFECTS ON THE SCALE DEPOSITS IN PIPE FLOWS

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Abstract. *The formation of scale on the internal surfaces of ducts, valves or heat exchangers is the main reason for the loss of efficiency in many industrial applications. The development of mitigation technologies becomes crucial for a long-term successful operation. However, the methodology currently employed, i.e., the injection of chemical inhibitors or mechanical removal, are costly and ineffective. In order to advance new understanding with regard to this problem, an experimental campaign was carried out to investigate the influence of flow dynamics on the deposition of calcium carbonate (CaCO3) in circular ducts. Within the scope of this work, the calcium carbonate deposition rate was measured for different Reynolds numbers and test times. The experiments have been conducted at the Multipurpose Flow Loop, which operates in open circuit and is equipped with 70 m long pipes of different inner diameters. Five different total flow rates were investigated: 300, 450, 600, 750 and 1000 litres per hour. Each experimental run lasted for 90 minutes, after which the test sections were dried at ambient temperature and the cleaning solution was pumped into the flow loop. The scaling thickness along the tube was measured and the deposits characterized by the scanning electron microscope (SEM). The work also discusses the joint contributions for the measured pressure drop along the pipe as a result of three different effects: i) the increase in surface roughness due to the calcium carbonate deposition, ii) the decrease in the effective diameter of the tube, which varies along the pipe, iii) and the additional drag imposed by precipitated solid particles in suspension in the bulk flow. The type of roughness created by the deposition process is also investigated, as well as its growth. The experimental results allow the characterization of the changes in the friction factor with the increase in the Reynolds number. The calculated roughness factors have been related to the saturation indexes along the pipe.*

Keywords: *scaling, turbulent pipe flow, magnetic field, experiments*

1. INTRODUCTION

Scaling is a problem typically found in many industrial applications, ranging from biomedical to oil exploration and production. Although many works have been devoted to the subject, the existing intricate relations between the thermodynamic predictions, the kinetics of the chemical reactions and the flow dynamics are still poorly understood (Zhang et al. 2001). Most of the data available in literature were obtained from small mixing vessels or capillary pipe (tube blocking tests) experiments. Typically, these experimental results bare no dynamical similarity with real industrial applications.

The predictive models used by the oil industry rely essentially on thermodynamics and capillary tube blockage tests. The persistent high number of equipment failures due to fouling, especially in carbonate reservoirs oil fields, establishes an urgent need for research and improved technological solutions.

The purpose of the present work is to conduct large scale turbulent pipe flow fouling experiments to investigate the influence of flow dynamics on the deposition of calcium carbonate (CaCO3). For this purpose, four different Reynolds numbers have been investigated and the resulting rough surfaces created by the calcium carbonate deposition have been characterized. The experiments have been conducted at the Multipurpose Flow Loop, which operates in open circuit and is equipped with 70 m long pipes of different inner diameters. Each experimental run lasted for 90 minutes, after which the scaling rate for each Reynolds number could be calculated. The scaling thickness along the tube was measured and the deposits characterized by the scanning electron microscope (SEM). The work also discusses the joint contributions for the measured pressure drop along the pipe as a result of three different effects: i) the increase in surface roughness due to the calcium carbonate deposition, ii) the decrease in the effective diameter of the tube, which varies along the pipe, iii) and the additional drag imposed by precipitated solid particles in suspension in the bulk flow.. The type of roughness created by the deposition process is also investigated, as well as its variation along the pipe length. The calculated roughness factors have been related to the saturation indexes along the pipe.

In general, the occurrence of inorganic scales is influenced by several factors such as: pressure, temperature, flow rate, local roughness, and presence of suspended solids, among others. Under reservoir conditions, oil flows along with gases (hydrocarbons) and water, called formation water. This aqueous solution contains many dissolved ions and CO_2 which, due to temperature and pressure conditions, are in equilibrium and thus fully dissolved in the liquid phase. During the well exploration process, the pressure decrease along the production line changes the equilibrium condition, favouring the precipitation of certain salts, such as barium sulfate (BaSO4), strontium sulfate (SrSO4), calcium sulfate (CaSO4) and calcium carbonate (CaCO3), which is the most common type of inorganic scale observed.

The use of enhanced oil recovery techniques in wells encompasses the injection of water or gas, or water alternated with gas. Although this benefits the increase in oil production, it may cause the opposite effect, as the mixture of incompatible waters (formation water and injection water) implies a dramatic increase in the scaling potential. This problem tends to worsen for mature fields, as the production of water tends to increase.

Typically, the oil industry resort to the continuous injection of anti-scaling addition on the well, in order to control and mitigate the detrimental effects of scaling on the production. However, this is a high cost solution, which requires additional infrastructure and increases the complexity of the well design and operation. New techniques such as surface coatings and the use of ultrasound and magnetic devices are currently being tested with a view to provide a more efficient and lower-cost solution for the scaling problem.

The main contribution of the present work is to simulate the scaling phenomena on a larger scale than the previous results available in literature. These results were obtained in similar dynamical and chemical conditions and could be directly related to real field applications.

2. BRIEF LITERATURE REVIEW

Scaling mechanisms involve different phenomena such as nucleation, crystal growth, particle agglomeration and deposition. These processes are influenced by chemical variables such as pH, salt concentration and composition and also by mechanical variables as the local fluid dynamics, Reynolds number, turbulence effects and local pressure drop.

In order to isolate the aforementioned effects, many studies involving fouling were carried out on a small scale capillary or reactor tests. Its main feature is to monitor the physicochemical effects of the process as nucleation, pH, conductivity, crystal morphology, among others.

Al Nasser et al. (2013) applied the FBRM (Focused Beam Reflectance Measurement) technique to monitor the fouling and aggregation rate on line. For this purpose the authors used a bench experiment, made from a Becker with 300 ml of saline solution, thermally isolated, which was mixed at a frequency of 1100 rpm.

Wang et al. (2017) compared the efficiency of scale inhibitors in the presence of EOR (Enhanced Oil Recovery) products. Two different techniques were used: capillary tube blockage tests and static vessel. Both served to demonstrate that the presence of these products negatively affect the use of inhibitors, which has its efficiency reduced by 10 times. Pressure measurements were taken for the dynamic tube blocking tests.

The experiment by performed by Zhang et al. (2001) used a synthetic formation water to generate the calcium carbonate scale. His main concern was to monitor the pH and composition of the base fluid. The experimental apparatus used was made of stainless steel with an internal diameter of 3.04 mm and a length of 1 meter. The capillary pipe was connected to a pump that provided a flow rate of 90 ml/h, which represents a Reynolds number close to 12 (laminar regime). The initial internal pressure was constant in all tests. The pH of the solution was controlled through the mixture of CO_2 to the brine solution and the temperature was constant due to the fact that the tubing was immersed in a thermal bath at 70º C. The test was interrupted after the pressure difference between the points of interest was greater than one bar. The obstructed tube was removed at the end of the test, washed with a saturated CaCO3 solution, in order to remove non-adhered salts, and then cut for analysis of the sample in a scanning electron microscope (SEM). A regular growth in the radial direction could be observed from the SEM images. The presence of polymorphs calcite and aragonite were also observed.

Andritsos and Karabelas (1991) also investigated the obstruction of pipelines by deposition of inorganic material; however, their research is done for the deposition of sulfites and not of calcium carbonate. The mixture of two incompatible brines forms the deposition. After mixing, the fluid enters the pipe, which is made of a plastic hose with an internal diameter of 13 mm and a length of 10 meters. There are also four test sessions made of flanged stainless steel tubes, and eight pairs of semi-annular coupons. The test sections were washed with distilled water at the end of the test and then dried. Coupons were analyzed in the SEM and the weight was used to calculate the deposition rate. According to the authors, the Reynolds number of this experiment varies from 3000 to 12000. This number is significantly higher than the tests by Zhang et al. (2001).

In this context, the present work aims to investigate the fluid dynamic effects on calcium carbonate deposition in a large-scale experimental apparatus, and thus fill some gaps in the current literature, since no large scale experimental apparatus was found in the literature.

3. EXPERIMENTAL SET UP

The present experiments were carried out at the Multipurpose Flow Loop located at the Well Technology Laboratory (LTEP) of the Interdisciplinary Center for Fluid Dynamics (NIDF). This flow loop has two circuits: i) a high pressure circuit, composed of three high pressure pumps, 100 m long stainless steel pipes of 1", 2" and 3" in diameter, that can reach respectively 420 bar, 310 and 260 bar with flow rates up to 3.5 m^3/h, and ii) a low pressure circuit, with 100 m long acrylic and stainless pipes of ½" and 1" in diameter, with maximum operational pressure of 12 bar and 20 m^3/h maximum flow rate. The temperature of the fluid can also be raised up to 80ºC. This range of operational conditions allows the experimental simulation of physiochemical, kinetics and flow dynamics characteristics that are within close similarity to field problems. Figure 1 shows an overview of the installations of the Multipurpose Flow Loop, showing the reservoirs on the right and the pipe circuits on the left.

Figure 1. Overview of the Multipurpose Flow Loop.

Water-based solutions of calcium chloride and sodium bicarbonate are prepared in separate tanks opened to atmosphere and mechanically stirred until the pH (measured daily) asymptotically stabilizes at an equilibrium value. The solutions are pumped separately by two progressive cavity pumps and the flow rates are measured by electromagnetic flowmeters prior to the mixing point at the pipe entrance. The working fluid saturation index is 3.4 and the brines' concentrations are shown in Table 1. According to Bezerra et al. (2013) these values are consistent with those found in operation, so there is similarity between the current tests and the real field application.

The pipe used in the present experiments were made of Plexiglas, in order to allow the visualization of the deposition process. The pipe was 70 m long and the internal diameter was 11 mm. Pressure measurements were carried out through 20 taps distributed along of the pipe length. Eleven small test sections were distributed along the pipe length to probe the deposited mass and to provide the samples to be analyzed at the Scanning Electron Microscope (SEM). At the beginning and at the end of the pipe there were valves for sampling the brine (working fluid) during the experiment.

The experimental conditions encompass five different Reynolds numbers, namely, 10,600, 16,000, 21,300, 26,600 and 35,500. The tests lasted for two hours.

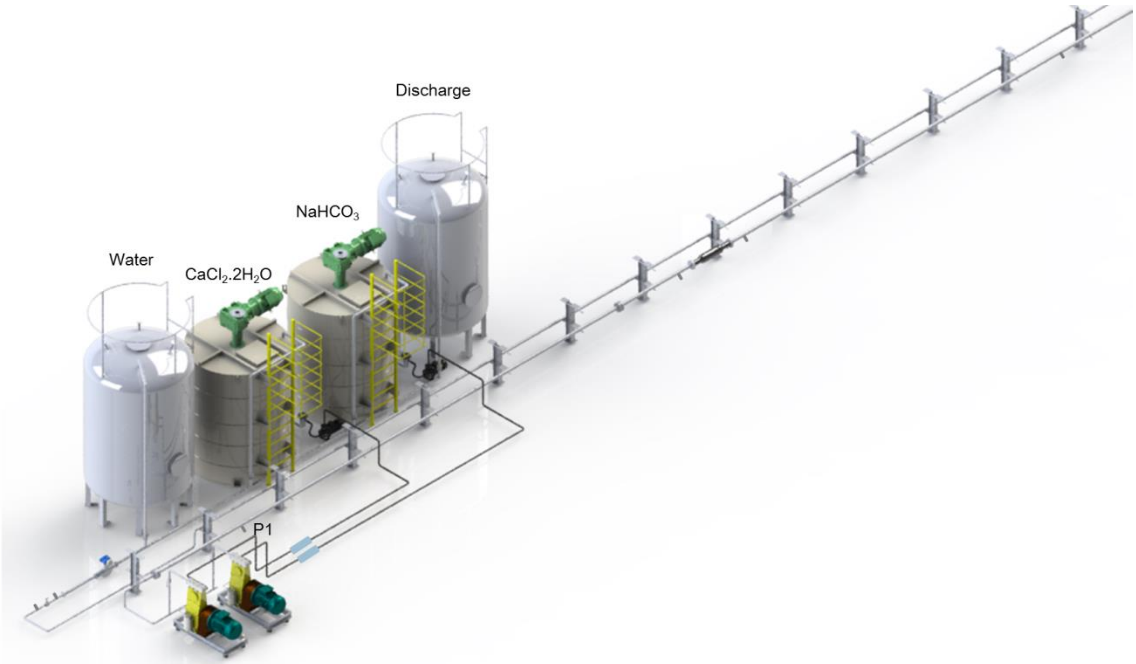

Figure 2. Schematic view of the experimental apparatus.

Table 1. Composition of the brines. Saturation index is 3.4.

	Concentration (g/l)	Molarity (mol/l)	Conductivity (mS/cm)	pH
$CaCl_2$	7,35	0,05	9,5	7,2 – 7,6
$NaHCO_3$	12,6	0,15	10,87	9,1 – 9,3

4. RESULTS

Figure 3a shows the variation of the deposited mass along the line. It is interesting to note that the initial test sections present a greater mass of deposited material, which decreases along the line until reaching a stabilization zone at 30 m. Such a tendency can be explained by the fact that the initial length of the pipe is closer to the injection of the two salts, so there is the highest concentration of the mixture. As this working fluid flows through the pipe, scaling deposition occurs, thus decreasing the concentration along the line.

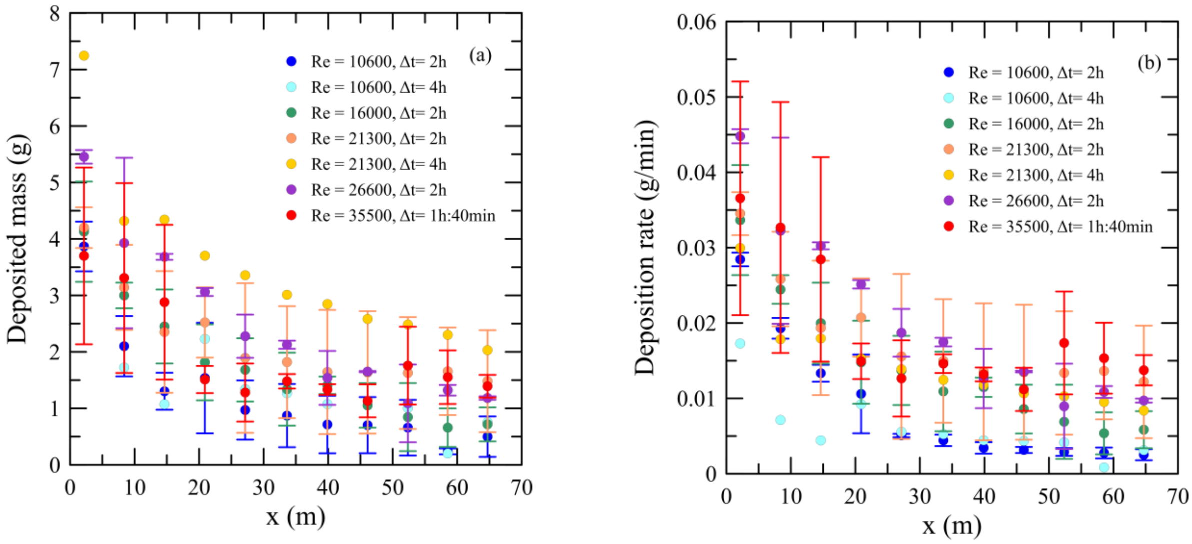

Figure 3. Scaling pattern along the pipe length: (a) deposited mass and (b) scaling rate.

Figure 3a also shows a tendency that the higher the flow rate, the greater the deposited mass, for tests with equal time interval. In order to normalize the results a fouling rate was calculated, taking into account the duration of each experiment. The result is shown in Figure 3b. Despite of that, the highest Reynolds test does not follow this trend, because one of the test replica was harmed by the mass low deposition and scaling weakness.

This scaling pattern is in good agreement with the results provided by Zhang et al. (2001) for a gas lift system in real field application.

From the pressure drop measurements along the pipe, and considering the effective diameter estimated from the measurement of the scaling thickness, the Colebrook equation (Eq. 1) has been used to calculate the friction factor and the roughness scale along the pipe.

$$\frac{1}{\sqrt{\lambda}} = -2log(\frac{\epsilon}{3,71D} + \frac{2,51}{Re\sqrt{\lambda}}) \quad (1)$$

For the friction factor calculation, density and viscosity of the fluid have been respectively measured and calculated considering the volume faction of solid particles.

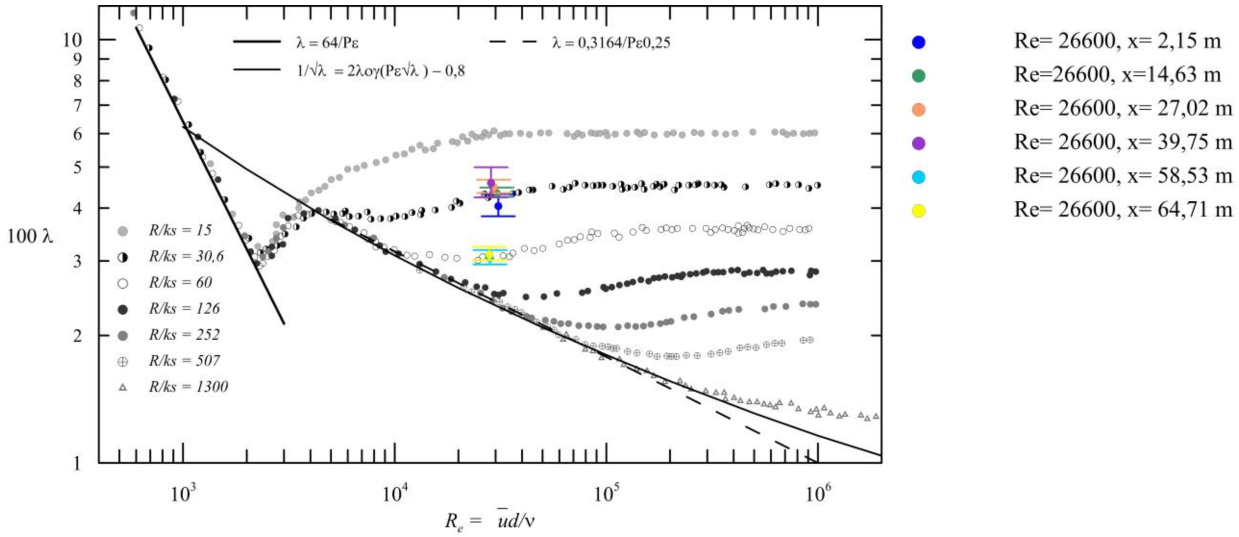

Figure 4. Friction factor measured for different positions along the pipe length for Re = 26600, Δt = 2h.

Figure 4 shows that for the 2-hour long tests, the calcium carbonate surface roughness for the first stages of the pipe follows a R/k_s =30.6 behaviour, whereas this value decays for R/k_s = 60 for the final stages of the pipe. Indeed, for the first 30 meters of the pipe length, scaling is dominated by ionic deposition, giving origin to the calcite crystal structure, as shown in Figure 5a (left).

Characterized by a cubic shape, calcite is the most stable polymorph of calcium carbonate. This cubic structure piles up as a pine tree, generating a large surface drag. For the downstream sections of the pipe, as the brine concentration decreases, the crystal structure changes to the vaterite polymorph, which is more round-shaped, as can be seen in Figure 5b (right). For the region downstream of the middle of the pipe, the surface roughness thus reaches a lower value, which is quite rough in comparison to the initial smooth surface pipe.

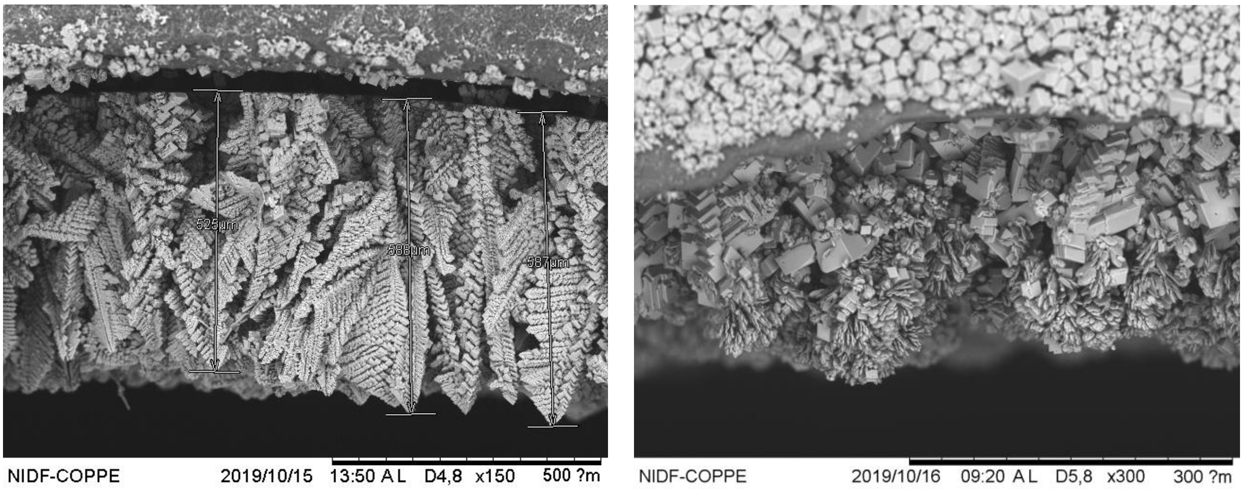

Figure 5.Typical structure of the deposited calcium carbonate: calcite (left) occurs on the first 30 m of the pipe length and vaterite (right) occurs on the latter section of the pipe.

5. CONCLUSION

The results obtained in the present work contribute in an original way to the characterization of the surface caused by the deposition of calcium carbonate in turbulent pipe flows.

The main innovation provided by this work is a pilot scale experimental apparatus. Comparatively the ratio between Length and Diameter (L/D) of this apparatus is around 3340 whilst that one performed by Zhang et al. (2001) is approximately 80. Thanks to this bigger ratio, experiments can be performed with a greater variation of Reynolds Number, similar to those ones achieved by Oil and Gas Industry.

Other important contribution is related to the measurement method of the scaling, which was done by Scanning Electron Microscope (SEM). This method allowed the recognition of the calcium carbonate structure and an accurate scaling thickness evaluation. Due to this, the friction factor was properly measured. This kind of measurement was not did in similar works.

For the industry, this data might provide correlations to predict the differences in deposition throughout the production and in different equipment, as well as to investigate the changes in crystal structure provided by the use of anti-scaling fluids.

In addition, the deposition rate, deposited mass and pressure information provide data that can be used for the validation of kinetic and dynamic predictive models.

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4. RESPONSIBILITY NOTICE

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