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ESSENTIAL PARAMETERS FOR MAGNETIC SCALE INHIBITION Part-1

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ABSTRACT

Kinetics of calcite scale deposition under the influence of magnetic field is reported in this article. The reduced deposition rate is believed to depend on many parameters. In this part of study the effect of flow rate, residence time of flowing fluid and scale forming ions under magnetic field and material of construction of tube were considered. Dynamic pressure build up in the flow loop indicated narrowing of effective tube diameter due to scale deposition. It is evident that longer residence time of scaling ions within magnetic field has higher scale inhibition effect. Fluid flow rate and magnetic hysteresis also affect the scale deposition rate. Scale formed under optimum magnetic coverage is exclusively aragonite scales whereas at weaker magnetic coverage yielded predominantly calcite scales. Comparison of flow study under identical condition shows that inhibition effect is better in electrically conductive copper tube than non-conductive plastic tube. The study concludes that magnetic scale inhibition is a feasible solution for calcite scaling problem. Magnetic flux density, magnetic permeability of the tube's material, exposure time, charge density of the dipoles and flow rates are some of the essential parameters need optimization based on the application.

Keywords: Magnetic scale inhibition, scale deposition, flow studies, crystal morphology.

INTRODUCTION

Application of magnetic field to prevent mineral scaling is one of the most controversial and least understood techniques among all scale control techniques. Although the technology has been around for nearly a century and considerable amount of laboratory work and field application are reported, claiming its effectiveness in reducing $CaCO_3$ and paraffin wax scaling, no convincing theory or mechanism is established that could help reliable candidate selection and treatment design. Most authors believe that scale inhibition is due to direct effect of magnetic field on the nucleation and crystallization process (Higashitani *et al*., 1993; Dalas and Koutsoukos, 1989; Benson *et al*., 1997; Nilson, 1999). While some observed that the effects may actually be due to chemical inhibition of the scale due to gradual release of inhibitory metal ions from the device itself, such as zinc, iron, or possibly copper (Welder and Partridge, 1954; Busch *et al*., 1986; Herzog *et al*., 1989; Lewis and Raju, 1997; Söhnel and Mullin, 1988). Availability of field implementation data is limited. However, its successful application in Tinggi offshore field of Malaysia is worth mentioning (Rahim and Slater, 2003).

The major drawback of magnetic technology are complicated physicochemical phenomena that occur simultaneously with no supporting theoretical model and the difficulties in getting reproducible results on a laboratory scale. However based on the conducted experiments, the principal operating conditions suggested are (a) the flow must be perpendicular to the applied magnetic field and the field strength should be at least 150 mT for successful treatment along with relatively high flow rates and long residence times, depending on the experimental conditions (Kobe *et al*., 2002).

When charged moving particles such as calcium and carbonate ions and dipolar compound ($CaCO_3$) are subjected to magnetic field, they are exposed to the following forces which may affect ionic association, nucleation and crystallization process of the scale forming ions.

Direct Magnetic Force-The Magnetic flux inside the tube generates a force on moving charged particles that could be derived from Lorentz's Law. The Lorentz orthogonal force is the result of the vector product of magnetic force and the flow of charged particles:

$$\vec{F} = \vec{V} \times \vec{B} \quad Newton$$

where V is the velocity of the charged particles along the tube and B is the flux density of the magnets inside the tube. The polarity of the particles is an indication of the direction of their movement. The Lorentz force has opposite directions for two particles charged with opposite polarity, moving at the same direction. It repels charged particles with opposite polarity into opposite direction whilst the electrostatic force attracts charged particles of opposite polarity. Thus, for the oppositely charged particles moving at the same direction:-

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Net force = (Lorentz Force – Electrostatic force) and Magnet*ic force* ∝ *Fluid Velocity x Magnetic flux density*

Since the Lorentz force direction changes as the polarity of the charged particles changes, the positive and negatively charged particles get separated. The Separation of moving charged particle and the distance they travel before colliding the tube wall and with each other, depends on magnetic flux density, electrostatic attraction and horizontal velocity of the fluid. As seen from the Lorentz Law formula, the force is zero at still charged particles. This means that the particles that get stuck to the pieces of scale at the tube, are exposed to zero Lorentz force.

The Lorentz force on moving charged particles generates acceleration in reverse proportion to the mass of the charged particles, according to the Newton's second law. The resultant acceleration leads to a velocity vector towards the walls, orthogonal to the fluid velocity. The wider the tube, the higher is this orthogonal velocity. Hence, the diameter of the tube and the velocity of the charged particles have direct effect on the separation force.

Magnetic hysteresis - When an external magnetic field is applied to an atomic or molecular dipole, they align themselves with the external field. Even when the external field is removed, part of the alignment will be retained which is magnetic hysteresis. This effect is expected to play a role on the on orientation of nascent $CaCO_3$ dipolar molecules during crystallization process, thus, helping the linear orientation of the molecules.

Kinetic force- Once the crystals are formed and grew large enough to deposit, the rate at which they would stick to the tube wall and reduce effective tube diameter would depend on the type and homogeneity of crystals and the kinetic force of the fluid. If the fluid velocity or kinetic force is strong enough, the scale flocks have week adherence tendency, they will be flushed out of the tube and less deposition will take place.

In this part of the article, we present our investigation results of the effect of (1) magnetic flux density and exposure time, (2) fluid velocity and (3) the material of construction of tube in controlling scale inhibition within a magnetic field under dynamic condition. To study the scaling behavior of supersaturated salts in flowing condition and under perpendicular magnetic field, a dynamic tube block apparatus was built and small units of cylindrical magnets were used to study various forces playing role in scale inhibition.

In a tube flow the scale deposition undergoes three distinct phases. First phase is the initiation phase in which a scale nucleation takes place and a few molecular level of scale is deposited. The second phase is the build up phase in which the scale crystals slowly adhere to the pipe wall, consolidate through crystallization process and start reducing the tube diameter and the third phase is the scale particles deposit on the pipe at a rapid rate, reduced pipe diameter and increase flow pressure rapidly. In our experiments we considered 25 psi differential flow pressure as the benchmark for development phaseI upto which fluid flow can be continued and 50 psi as the benchmark for near choking condition of the tube.

MATERIALS AND METHODS

Small units of cylindrical, high magnetic flux density, permanent magnets of alloy materials were specially fabricated for our investigations. Dimensions, and flux directions are shown in figure 1. High pressure plastic and copper tubes (both non-ferrous materials) of 3.5 mm inner diameter were chosen for fluid flow to provide maximum magnetic flux with minimum loss.

A series of cylindrical magnets formed a tube that could hold the experimental tube within its magnetic field while the field remains perpendicular to the direction of fluid flow. To measure the flux density of the magnets within the fluids inside the tubes, and its decay rate along central axis, a simple laboratory set up was arranged and Leybold Tangential B-Prob Tesla meter was used. The results (Fig. 3) were verified with theoretical values calculated from the equation given below. Reduction factor for peak magnetic flux density, used for copper and plastics in compared to air are 1.4 and 1.6 respectively.

The well known Tesla's equation for calculating flux density of cylindrical magnets along its central axis is:

$$B = \frac{B_r}{2}\left\{\left(\left(\frac{L+x}{\sqrt{R^2+(L+x)^2}}\right)-\left(\frac{L+x}{\sqrt{r^2+(L+x)^2}}\right)\right)-\left(\left(\frac{x}{\sqrt{R^2+x^2}}\right)\right)-\left(\left(\frac{x}{\sqrt{r^2+x^2}}\right)\right)\right\}$$

where:
L = Length of cylindrical magnet
2r = Inner diameter of cylinder
2R = Outer diameter of cylinder
x = distance from the center of the magnet
Br = Flux Density of the type of magnet used for this experiment
B = Total flux density of the cylinder at point x

The flow studies were conducted on a tube blocking flow set up, with accurate pressure detection and data acquisition facilities. Two high magnetically permeable tube materials were used, HDPE plastic and copper. With the help of two precision syringe pumps, cation (Ca^{2+}) and anion (CO_3^{2-}) solutions are pumped, which are pre-heated and enters the flow tube upon immediate comingling through a T-joint. The flow tube is covered with pre-determined number of strong permanent magnets to cover a specified area (Fig. 2). The magnets exert uniform magnetic field perpendicular to fluid flow. Many small cylindrical shaped permanent magnets were used

Table 1. Details of the flow study experiments.

Experiment Number	Tube material	Length of magnet	Length of tube	Magnetic coverage	Ca^{2+} solution flow rate	CO_3^{2-} solution flow rate
P-2+2-0	Plastic	0	3.3 m	0	2 ml/min	2 ml/min
P-2+2-30	Plastic	1 m	3.3 m	30%	2 ml/min	2 ml/min
P-2+2-60	Plastic	2 m	3.3 m	60%	2 ml/min	2 ml/min
P-4+4-60	Plastic	2 m	3.3 m	60%	4 ml/min	4 ml/min
P-6+6-60	Plastic	2 m	3.3 m	60%	6 ml/min	6 ml/min
C-2+2-0	Copper	2 m	3.3 m	60%	2 ml/min	2 ml/min
C-2+2-60	Copper	2 m	3.3 m	60%	2 ml/min	2 ml/min
C-4+4-60	Copper	2 m	3.3 m	60%	4 ml/min	4 ml/min
C-6+6-60	Copper	2 m	3.3 m	60%	6 ml/min	6 ml/min

Legends: P (plastic tube), C (Copper tube), 2+2, 4+4 and 6+6 (flow rate of anion and cation solution @ 2, 4 and 6 ml/min each), 0, 30 and 60 (0%, 30% and 60% of the tube length is covered by magnet.

Table 2. Experimental fluid dynamics.

Net flow rate	Flow velocity	Exposure time 1 m mag coverage (30%)	Exposure time 2 m mag coverage (60%)	Reynold's No. (Re)
4 ml/min	0.007 m/s	143 sec	286 sec	85
8 ml/min	0.014 m/s	71.4 sec	142.8 sec	177
12 ml/min	0.021 m/s	47.6 sec	95.2 sec	255

adjacent to each other and oriented in the same magnetic direction. In this experiment the variables were tube material of construction, magnetic coverage area, flow rate and exposure time under magnetic field. In order to investigate the effectiveness of magnetic field coverage, flow velocity, exposure time and tube material, nine flow studies were conducted with identical tube length (3.3mt) and at 158^{o}F temperature. The Cation solution (1000ppm) was prepared with calcium chloride and the anion solution (1000ppm) was prepared with sodium carbonate. The solutions were filtered before use and flown at equal proportion in each experiment, thus final concentrations of Ca^{2+} and CO_3^{2-} in the brine were 500ppm each. Differential pressure across the flow tube was recorded at every 1 minute and plotted against time of flow. End points of the experiments were either rapid increase of differential pressure or about 180 hours of flow, whichever was less. The samples were dried at 70^{o}F under vacuum and subjected to scanning electron microscopy. Table 1 presents the detail of experimental conditions under which flow studies were conducted. Table 2 presents the residence time of scaling fluids under direct magnetic field and Reynold's number of flow experiments. For morphological analys, scale deposits from inside the tube were carefully collected from experiments **P-2+2-0**, **P-2+2-30** & **P-2+2-60.**

RESULTS AND DISCUSSION

Strength of the magnets: Measured and theoretical values of flux density exerted by a single magnet, covering plastic and copper tube, are represented in figure 3. It also shows the flux decay along the central axis. It is evident that form this figure that the measured flux density is slightly higher for both the tubes compared to the calculated values. It also shows that the maximum available magnetic flux density inside the copper tube is 160mTelsa and the plastic tube will experience about 137 mTelsa magnetic flux at its centre. In both cases the flux decays to near zero at a distance of 12cm.

Effect of magnetic field: Type of scale formation and rate of scale deposition on the tube wall define the rate at which the tube diameter is reduced and differential flow pressure (ΔP) is increased. Thus the rate of change of ΔP is the indirect indication of scale build up rate inside the tube, which are plotted against duration of flow in figure 4 -11. From these figures two general observations can be made. (a) Three distinct pressure build up phases are seen in most of the plots, the scale initiation or nucleation phase of very slow increase of pressure, followed by a moderate rate of pressure increase which is the scale build up phase and finally the rapid pressure build up stage at which the tube gets nearly blocked by deposited scale crystals. These phases are highlighted by dashed lines for comparison of the slopes and hence scaling rate. (b) Saw tooth pattern is observed in all the plots due to fluctuation of flow pressure, resulting from continuous building up and flushing out of blocking scale materials. This pattern is more pronounce in experiments with copper tube.

Scale build up in plastic tube with magnetic coverage of 0, 30 and 60% of the tube length are presented in figure 4. In all these tests the net flow rate remained constant at 4

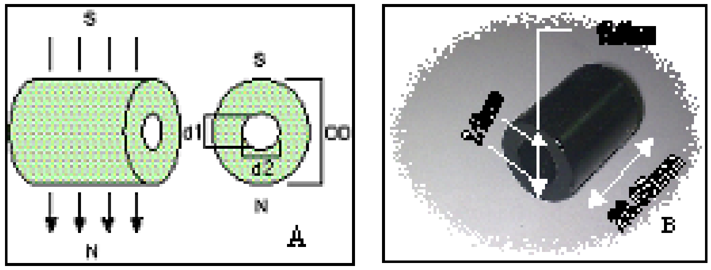

Fig. 1. Cylindrical magnets used for the study. A-Schematic. B-Actual image.

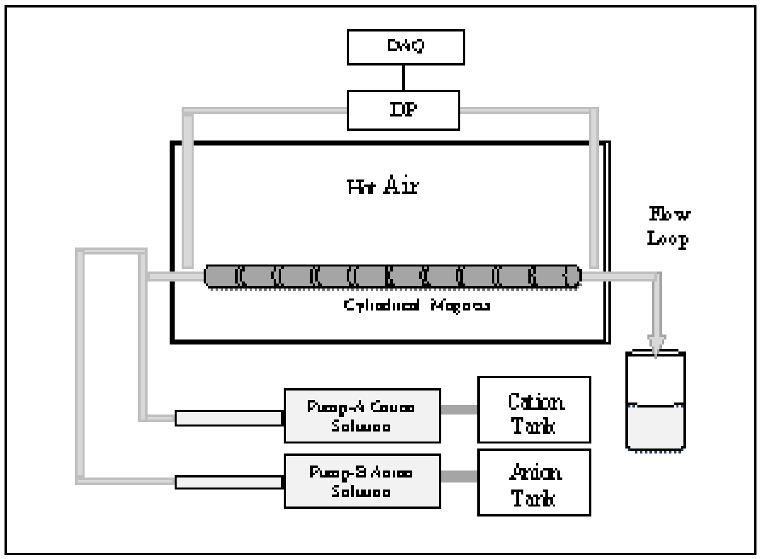

Fig. 2. Schematic of magnetic scale inhibition flow set up.

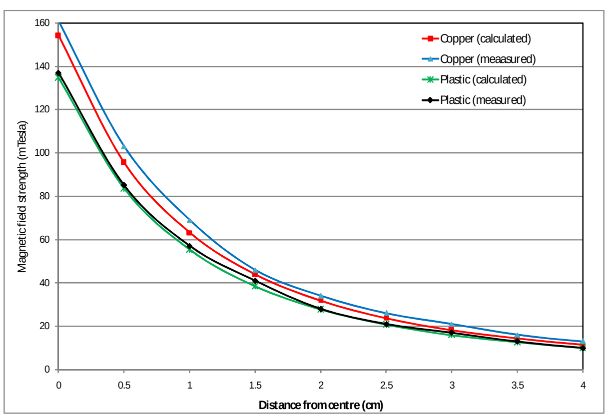

Fig. 3. Field strength decay of a single magnet covering flow tube.

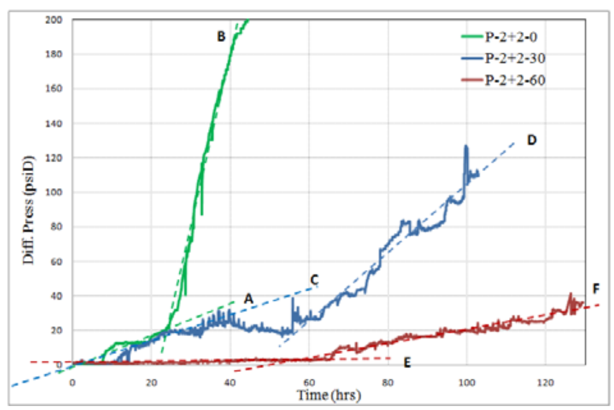

Fig. 4. Effect of magnetic field coverage and exposure time on scaling in plastic tube.

ml/min. The figures clearly show the influence of magnetic field on scale build up rate. In the flow condition without magnetic field (P-2+2-0), the ΔP across the tube developed rapidly after a small initiation period of 8 hours and within a period of 40 hours the tube was almost blocked. In case of P-2+2-30, in which the residence time of the fluid within the magnetic field is 143 sec, the initiation phase is stretched to about 11 hours and the development phase continued upto 58 hours and the blocking phase appeared at 75 hours. A further impressive result is achieved with 60% magnetic coverage (P-2+2-60). In this case the fluid has the residence time of 286 seconds within the magnetic field. It could be seen from the figure that the initiation phase, is extended to nearly 68 hours, a 8 fold increase compared to no magnetic field and nearly 6 times scaling inhibition

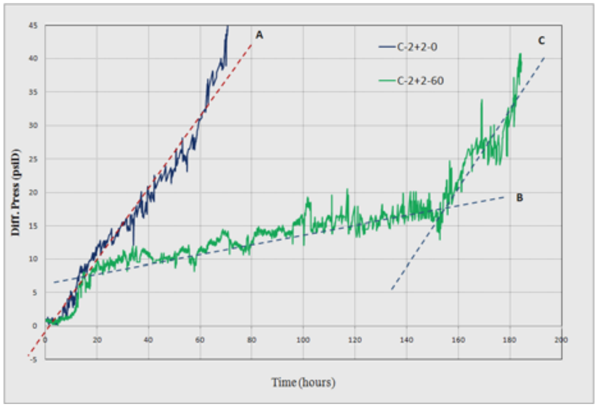

Fig. 5. Effect of Magnetic flux on scale inhibition in copper tube.

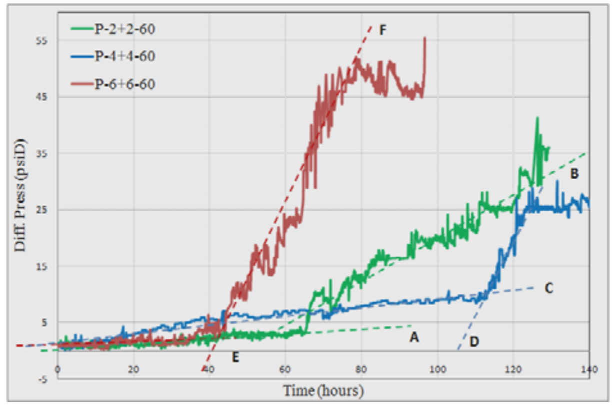

Fig. 6. Effect of flow rate and flux time on scale deposition in plastic tube.

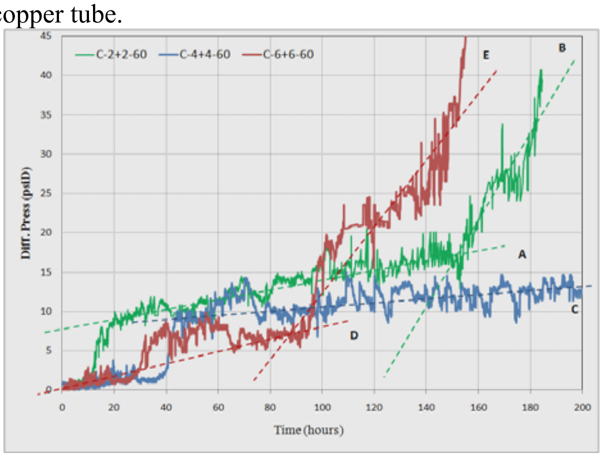

Fig. 7. Effect of flow rate on scale deposition in copper tube.

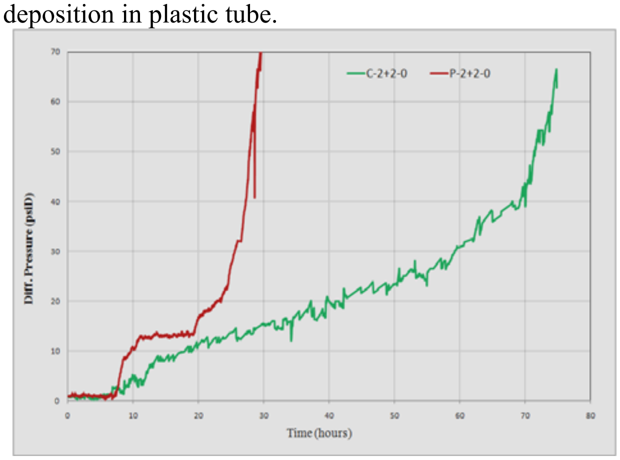

Fig. 8. Comparison of scale deposition rate in plastic and copper tube without magnetic coverage.

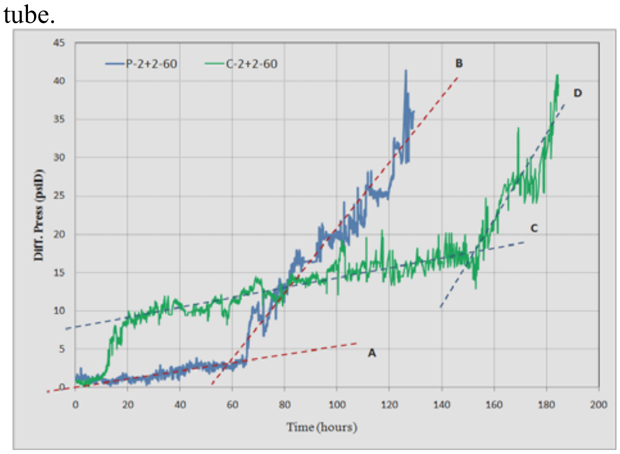

Fig. 9. Comparison of scale deposition rate in plastic and copper tube at 4 ml/min flow rate and 286 sec magnetic exposure time.

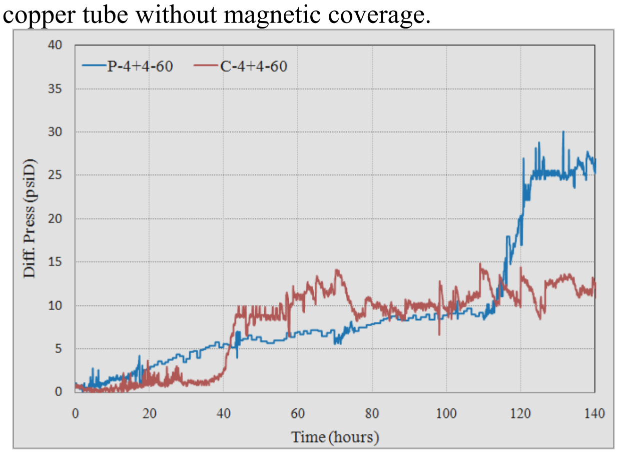

Fig. 10. Comparison of scale deposition rate in plastic and copper tube at 8 ml/min flow rate and 143 sec.

compared to 30% tube coverage. This phase was followed by a slow build up phase, which took nearly 122 hours to reach 25 psi only, indicating reduced scale deposition rate is by a factor of 5. Figure 5 represent scale build up rate in copper tube without magnetic field (C-2+2-0) and with magnetic field (C-2+2-60). It is evident from these results that (a) scale build up without magnetic field is much faster compared to when 60% of the tube is covered with magnet, (b) the initiation phase is smaller compared to plastic tube, which may be attributed to higher roughness of surface of copper tube compared to plastic tube and (c) the control on scaling rate cannot possibly be entirely due to the release of copper ions from the tube itself, as apprehended by some authors (Lewis and Raju, 1997; Söhnel and Mullin, 1988). Crystal morphology of deposited scales analyzed through SEM (Fig. 12, 13, 14)

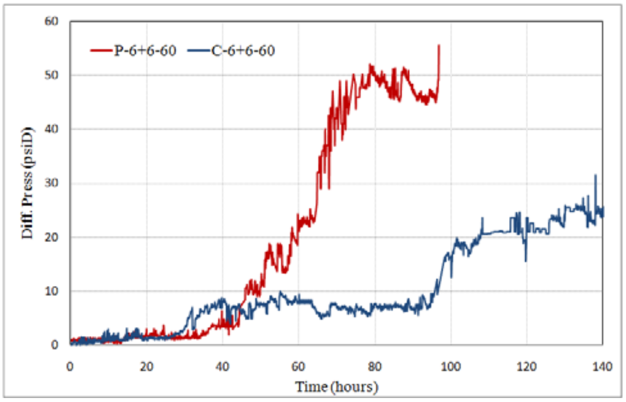

Fig. 11. Comparison of scale deposition rate in plastic and copper tube at 12 ml/min flow rate and 95 sec magnetic exposure time.

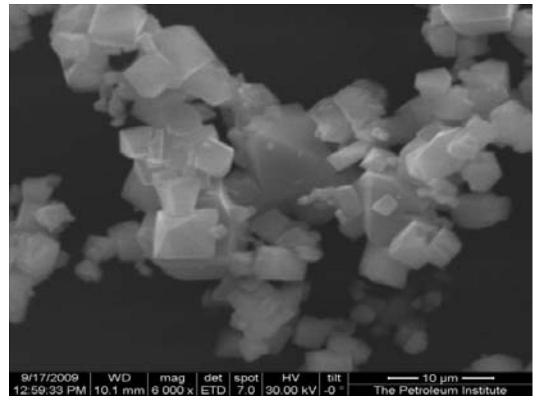

Fig. 12. SEM image of scale crystals without magnetic field (P-2+2-0).

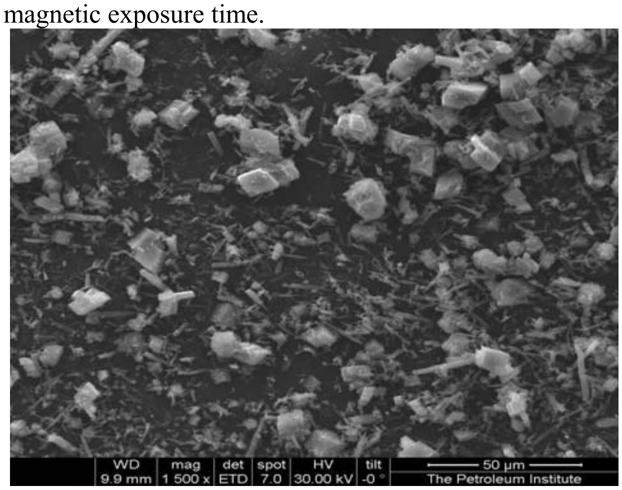

Fig. 13. SEM image of scale crystals with 30% magnetic coverage (P-2+2-30).

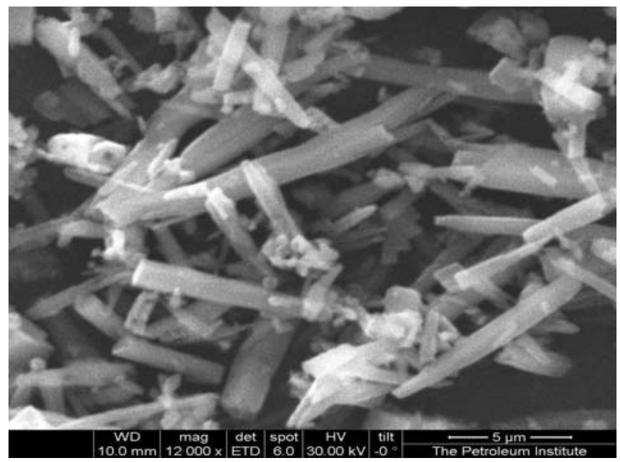

Fig. 14. SEM image of scale crystals with 60% magnetic coverage (P-2+2-60).

demonstrate the difference of crystal types under three flow conditions. The scale crystals without magnetic field are block shape purely calcite scale as expected (Fig. 12).

The scale type obtained with 30% magnetic coverage (P-2+2-30) is found to be mixed aragonite (needle shape) and calcite scales whereas predominantly aragonite scale is obtained when magnetic coverage is extended to 60% of the tube length (P-2+2-60). Observation from figure 4 and 5 suggest that the length of the magnetic coverage and thus the time during which the fluid is exposed to the magnetic field (Table 2) is important for scale inhibition process. This delay in scale formation, deposition and tube blocking could be safely attributed to the Lorentz force which is the main motive that prolongs the scaling process. It repels the positive and negative polarities and works opposite to electrostatic attraction between them. However, the Lorentz force is not the only exerted force in this field, but, there are others like the mechanical pressure that pushes the particles forward, the viscous resistance force of the fluid and the random rotation of the dipoles. All these forces possibly work in unison and help in formation of needle type aragonite scales and prevent formation of regular block shaped calcite. Thus the applied magnetic field not only delays the initiation phase by inhibiting dipole association but also prolong the building up phase by forming irregular shaped aragonite crystals which creates soft deposits instead of hard deposits created by regular shaped calcite crystals.

Effect of fluid velocity on scale deposition rate, under equivalent magnetic field is represented by figure 6 and 7. The experiments were conducted in plastic and copper tube at net flow rate of 4 ml/min (P-2+2-60, C-2+2-60), 8 ml/min (P-4+4-60, C-4+4-60) and 12 ml/min ((P-6+6-60, C-6+6-60). Table 2 shows that in all the experiments the flow is laminar (Reynold's number 85, 177 and 255 consecutively). It is evident from these plots that for both plastic and copper tubes, the experiments with net flow rate of 8 ml/min has shown best performance as far as delaying the appearance of the 3rd or blocking stage. This is followed by experiments with net flow rate of 4 ml/min and 12 ml/min flow rate. These findings suggest that two different mechanisms are influencing the deposition rate.

At higher flow rate, magnetic force or Lorenz's force is higher which helps to keep the ions separated and reduce deposition rate. At the same time at higher flow rate the residence time is shorter which minimizes the net magnetic effect. Also at higher flow rate the mechanical and viscous forces helps to flush out some of the loosely bound crystals. In case of 12 ml/min flow rate the ions and dipoles are under magnetic field for a very short period of time (85 seconds), which is possibly not sufficient to prevent calcite formation and since block shape calcite crystals form hard scales, even a higher flow rate may not be enough to flush out and delay the third stage. On the other hand, at 4 ml/min the ions are dipoles are experiencing longest residence time and producing mainly soft aragonite crystals, however the flow rate is not sufficient to flush them out of the tube. The intermediate flow rate of 8ml/min is possibly the optimized flow rate in which the magnetic force and residence time is enough to create soft aragonite crystals as well as sufficient mechanical drag to flush out some of the deposited scales so that the onset of the third phase is delayed sufficiently.

Influence of tube material: Comparison of pressure plots of flow through plastic and copper tubes under identical condition are presented in figure 8, 9, 10 and 11. Figure 8 which compares control experiments (with no magnetic field) in plastic and copper tube shows a significant difference in the scale deposition rate. Rate of scale deposition is much faster in plastic tube compared to copper tube. This phenomena may be attributed to the fact that dissolution of copper as copper ion in micro-scale may be the affecting the scaling process as observed by Sohnel and Mullin (1988). Comparative plots under magnetic field show that the rate of pressure build up in the initial phase is higher in case of the copper tube compared to the plastic tube. In the later phase, however, the rate of pressure build up is much reduced in the copper tube. This could be attributed to the fact that electrical conductivity of copper being much higher than plastic, weaken the effect of Lorenz's force, resulting in a faster neutralization of charge density of the ions and formation of scaling salt, as they get in contact with the surface of the copper. Besides, the smoother surface of the plastic tube, helps to slow down adherence of scale particles on the tube wall in the initial phase. In the later phase, due to the deposition of electrically non-conductive scale materials, the inner surface of copper loses its electrical conductivity and thus the Lorenz's force becomes dominant. Since the Lorenz's force is stronger in copper than plastic (Fig. 2), the rate of scale build-up and deposition is slower compared to the plastic tube. It is also possible that the longer building up phase in copper tube is due to the interference of released copper ions, by inducing further randomness on the crystal deposition process which facilitate formation of softer scale and prolong the building up phase, as evidenced from the experimental results.

The above observation supports the justification that the scaling process is a function of multi variable parameters. In addition to the parameters studied and explained above, we assume that the scale deposition rate and hence pressure build up is a function of tube radius, polarity of the scaling ions and temperature of the fluid. These parameters are planned for future study. From the experimental results and the above assumption the overall scale deposition rate under magnetic field may be modeled by the following formula:

Scale deposition rate = $f(B, \mu, t, V, C, r, T)$

Where:

B = Magnetic Flux Density and its orientation

μ = Magnetic Field Permeability (μ is different for plastic and copper)

t = exposure time

V = Velocity of the fluid

C = Polarity of the dipoles

r = radius of the tube

T = Temperature

CONCLUSIONS

From this study the following conclusion could be made:

1. Scale deposition rate is slowed down due presence of magnetic field.
2. Scale deposition rate is dependent on magnetic coverage area or residence time of scaling ion within the field.
3. Magnetic flux orient the scaling molecules and favors formation of needle like aragonite crystals which is less adherent on tube walls compared to calcite scales.
4. Higher velocity of fluids containing charged particles generates higher magnetic force which help to keep the scaling ions separated.
5. Higher resident time under magnetic field reduce scaling.
6. Optimization of magnetic coverage area or resident time under magnetic field along with optimum fluid velocity is essential for scale prevention.
7. Magnetic scale inhibition in electrically conductive copper tube is more effective than non-conductive plastic tube.

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