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Investigating the Lorentz Force Effect in Reducing Calcite Scaling in Pipe Flow

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ABSTRACT

In this work the effect of Lorentz force in reducing calcite scaling in plastic and copper pipes are studied. Traditionally two types of forces are considered for ionic interaction and the process of scale formation inside fluid pipes which are the electrostatic and mechanical forces. This research considers a third force that comes from an induced orthogonal magnetic field. The moving charged particles flowing through a pipe come under Lorentz force when the field is applied to the direction of flow. The effect of Lorentz force that works against the electrostatic attraction when two oppositely charged ions flow through a tube encircled by a magnetic field are mathematically derived and justified with laboratory tests. Magnetic field was applied perpendicular to the flow direction using strong cylindrical permanent magnets covering the tubes. Effect of flow rate, magnetic coverage area and magnetic field permeability of the tube materials on calcite scaling rate were studied through dynamic flow studies. Pressure build up in the tubes were measured as indicator of narrowing effective tube diameter due to scale deposition. It is seen that higher resident time of the scale forming ions within the magnetic field has significant scale inhibition effect. Flow rate of the liquid and magnetic hysteresis affect scale deposition rate too. Scale formed under optimum magnetic coverage is exclusively aragonite scales. Calcite scale is predominant at low magnetic coverage or no magnetic field. 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 for magnetic scale inhibition, magnetic flux density, magnetic field permeability of the pipe's material, exposure time, charge density of the dipoles, flow rate and the temperature are essential parameters and need optimization based on the application.

Keywords: Lorentz force, Magnetic scale inhibition, Dynamic scaling, Calcite scale deposition.

INTRODUCTION

Calcium carbonate or calcite scale deposition is one of the most common flow assurance problems encountered in oilfield operations impacting well production profile and efficiency of surface facilities. Efficiency of ancillary equipment such as heat exchangers, reverse osmosis membrane surface, cooling water systems, boilers, desalination plants, flue gas desulphurization systems, etc. are also impacted due to mineral scale deposition of which calcite is often the primary component (Balasubramanian et al. 2011).

Of the numerous scale mitigation techniques available in the industry, magnetic amelioration of calcite scale has drawn good attention mainly because of insignificant recurring expenditure and greenness of the technology. Although considerable amount of published works are available with claims of its effectiveness in reducing $CaCO_3$ and paraffin wax scaling, no convincing theory or mechanism could be found, that may help to design reliable remedial measure. The work of Lipus and Dobersek (1966) showed that the effect of magnetic field on enhancing the portion of aragonite crystals such that the crystals become less adhesive than calcite ones. It has been noticed that the crystals become more needle-like and thinner when the pipe is under magnetic effect. The magnet reduced the rate of scaling/hour significantly from exponential function to more like linear form. However, the physical reason behind this phenomenon has not been discussed in details. 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 P. G. 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; Sohnel and Mullin, 1988). Highly complicated physicochemical phenomena that occur, simultaneously with no supporting theoretical model and the difficulties in getting reproducible results on a laboratory scale has created confusion among scientific community about applicability and designing this otherwise attractive technology for large scale field application. The availability of field implementation data are also scares except the successful application in Tinggi offshore field of Malaysia (Rahim and Slater, 2003) which is worth mentioning. However based on the conducted experiments the principal operating conditions suggested by Kobe et al.(2002) are; (a) the flow must be perpendicular to the applied magnetic field and the field strength should be at least 150 mili-Tesla for successful treatment along the pipeline, and (b) with relatively high flow rates, and (c) long residence times depending on the experimental conditions

In the present work scaling behavior of supersaturated brines are studied under orthogonal magnetic field in multi-variable and dynamic conditions. Magnetic field is applied on the flowing fluid with the help of small units of cylindrical magnets. The crystal nucleation and bulk scale formation process are explained in view of electrostatic and Lorentz forces acting on them. The study was conducted with the help of a dynamic tube block apparatus and small units of cylindrical magnets were used to study various forces playing role in the scale inhibition process.

MATERIALS AND METHODS

Small units of cylindrical permanent magnets of alloy materials with high magnetic flux density, were specially fabricated for our investigations. Dimensions, and flux directions are shown in figure 1. High pressure plastic and copper pipes (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 conduit that could hold the experimental pipe 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-ProbeTesla meter was used to read magnetic strength within the pipes. Reduction factor for peak magnetic flux density, used for copper and plastics, compared to air are 1.4 and 1.6 respectively. Thewell-known Tesla's equation for calculating flux density of cylindrical magnets along its central axis is as given below:

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

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 specially designed tube blocking flow set up having accurate pressure detection and data acquisition facilities. With the help of two precision syringe pumps cation (Ca^{2+}) and anion (CO_3^{2-})containing fluids are pumped, which are pre-heated and enters the flow pipe upon immediate comingling through a T-joint. The flow pipe is covered with pre-determined number of strong permanent magnet to cover a specified portion of the pipe. The magnets exert uniform magnetic field at the pipe's width direction. Many small cylindrical shape permanent magnets were uses adjacent to each other to cover the pipe that were oriented at the same magnetic direction. In order to investigate the effectiveness of magnetic field coverage, flow velocity, exposure time and tube material, seven flow studies were conducted with identical tube length (3.3 mt) and at 158 ^{o}F. Cation solution (1000 ppm) was prepared with calcium chloride and anion solution (1000 ppm) 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-} through the flow tube were 500 ppm each in all the flow studies. End points of the experiments were either rapid increase of differential pressure or 180 hrs, whichever was less. Following are the description of the conducted flow studies:

Flow study 1 (FS-1) - Reference experiment in plastic tube without any magnetic coverage. Total flow rate was maintained at 4 ml/min (2 ml/min through each pump).

Flow study 2and 3 (FS-2 & FS-3) – These studies were conducted in identical condition as above but with 30% and 60% magnetic coverage of the plastic pipe respectively.

Flow study 4and 5 (FS-4 & FS-5) – These studies were conducted in plastic tube with 60% magnetic coverage and at total flow rate of 8 and 12 ml/min respectively.

Flow study 6, 7 and 8 (FS-6, FS-7 & FS-8) – These studies were conducted in copper tube of inner diameter same as plastic tube with 60% magnetic coverage and at total flow rate of 4, 8 and 12 ml/min respectively.

Scale sample from FS-1, FS-2 & FS-3 were collected, dried and subjected to scanning electron microscopic investigation.

Pressure build up during the flow is plotted against flow time and plotted in the flowing figures. Fig. 1 represents pressure build up in FS-1, FS-2 and FS-3, Fig. 2 represent the same for FS-3, FS-4 and FS-5, while Fig. 3 represents flow studies conducted in copper tube (FS-6. FS-7 and FS-8).

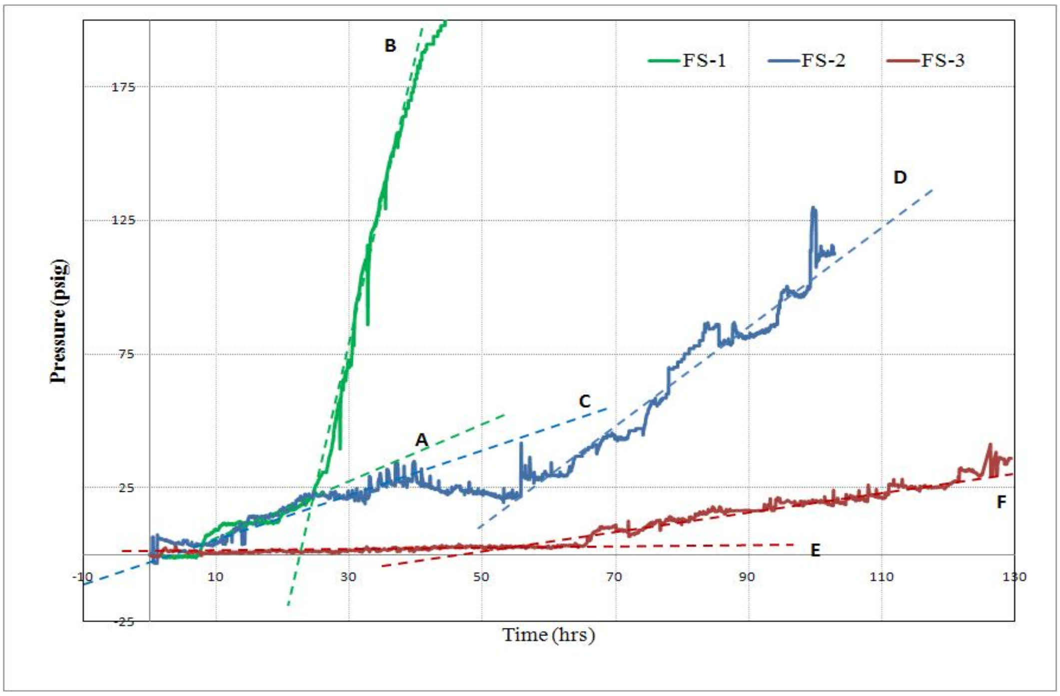


Fig.1. Effect of magnetic field coverage and exposure time on scale inhibition.

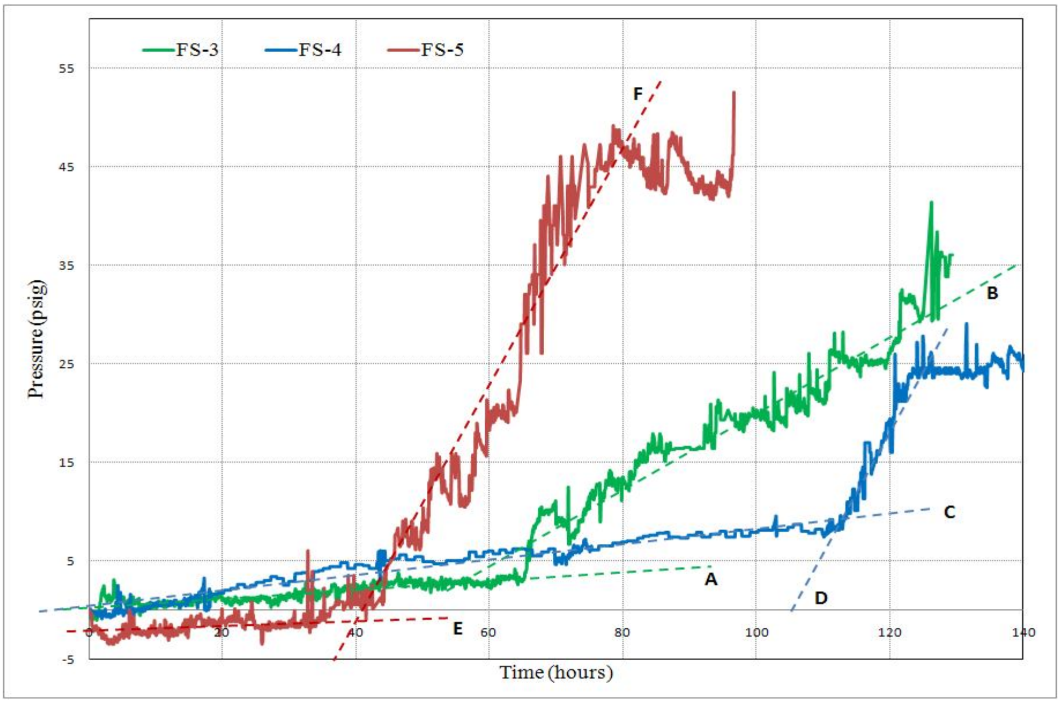


Fig.2. Effect of flow rate and flux time on scale deposition in plastic tube.

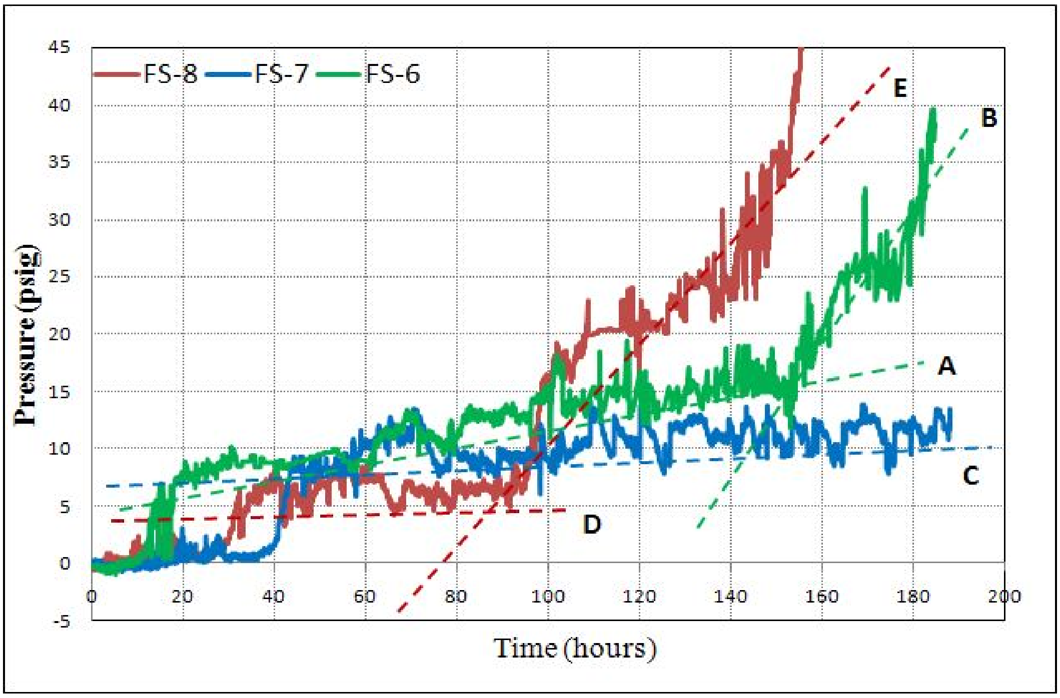


Fig.3 Effect of flow rate and flux time on scale deposition in copper tube

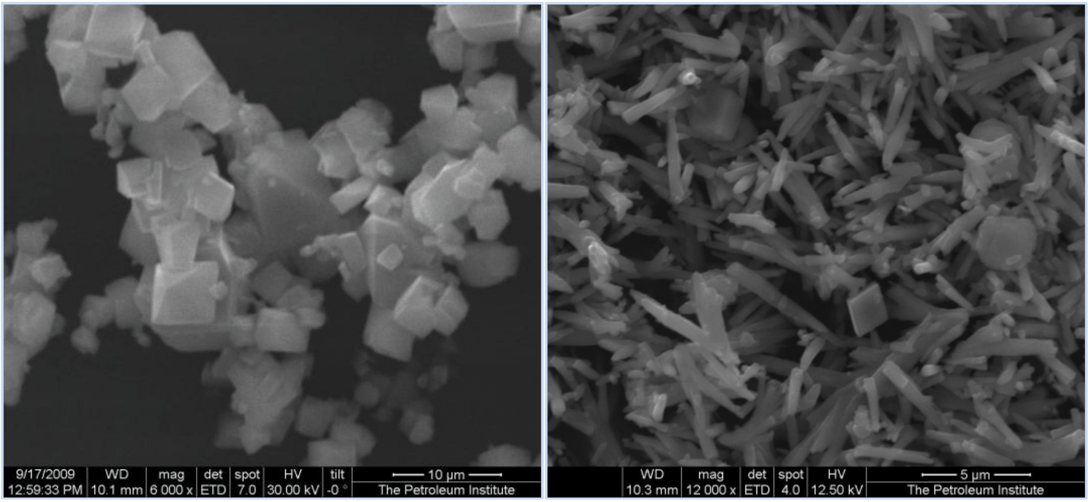


Fig.4.SEM images of scale crystals under (A) no magnetic field (calcite) and (B) under magnetic field (predominantly aragonite).

PROPOSED THEORITICAL MODEL

Dipoles with opposite charges attract each other similar to free ions. The attractive electrostatic force for two opposite charges in two dipoles has the magnitude of:

$$F_e = \frac{q_1 q_2 l_1 l_2}{r^4} \qquad \text{…………………..(1)}$$

The electro static charges are q_1 *and* q_2 and with length sizes of l_1 and $l_2$at a distance of *r*.

The magnetic flux inside the pipe generates a force on moving charged particles that could be driven from Lorentz's Law. The Lorentz orthogonal force is the result of the vector product of magnetic force and the flow of charged particles.

The magnetic flux (B) of the magnets is perpendicular to the fluid velocity (v_f). The positively and negatively charged particles floating in the fluid are exposed to the following force generated by Lorentz law.

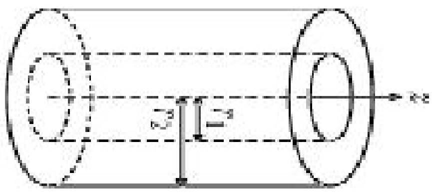
$$F_m = qv_f \times B \qquad \text{…………………..(2)}$$

The force (F_m) causes a centripetal acceleration.

$$a_c = \frac{v_c}{r} \qquad \text{…………………..(3)}$$

Where $v_c$the tangential velocity and *r* is the radius of rotation.

The resultant two velocities causes a helical motion of the charged particles inside the fluid. The positively charged particles cause right handed helical motion while the negatively charged particles cause left handed helical motion. Here the assumption is that the fluid has a constant velocity at every point of the pipe, which is not the case for fluids with high viscosity. It is because of the highest shear stress of the fluid close to the pipe wall, the fluid velocity close to the wall is much less than the velocity at the center of the pipe. One can consider the flow inside the pipe as moving cylinders (see figure below).



Each layer of the fluid has its own radius and velocity. Eq. 3 can be re-written for each layer as:

$$a_c(i) = \frac{v_c\,(i)}{r(i)} \qquad \text{……………………. (4)}$$

Where *(i)* represents individual layer

Each layer of the fluid keeps its portion of the charged particles in a helical motion and prevents them to move to the other layers. Depending on the fluid velocity and the density of the magnetic flux, the Lorentz force on the charged particle in each layer can be greater or smaller than the electrostatic attraction between the positive and negative charges. The overall motion of the charged particles inside the fluid is very complex when we consider the effect of fluid viscosity and magnetic flux inside each layer of the fluid. The motion of the charged particles strongly depends on the radius of the layer under investigation. As the radius becomes zero at the center of the pipe, the swirling flow disappears. This nonlinear motion of the charged particles along the diameter of the pipe is one of the probable cause of prevention of scaling in the pipe.

The experiments performed in the lab (explained in the following section) approve the above proposal that magnetic field perpendicular to the direction of the flow can overcome to the electrostatic attraction of the oppositely charged particles in the fluid. It also shows how the effect is sensitive to the velocity of the fluid.

It is important to pay attention to the polarity of the charged particles in Equation 2, which is an indication of the direction of their movement. As it is mentioned, Lorentz force has opposite directions for two particles, charged with opposite polarity moving at the same direction in the pipe. It repels charged particles with opposite polarity into opposite direction whilst the electrostatic force attracts charged particles of opposite polarity. Thus for opposite charged particles moving at the same direction:

Net electromagnetic force = (Lorentz Force – Electrostatic force)

Since the direction of Lorentz force changes, as the polarity of the charged particles change, the positively and negatively charged particles repel each other.

Separation of moving charged particle and the distance they travel before colliding with each other increases with increasing magnetic flux density and horizontal velocity of the fluid. As seen from the Lorentz's formula, the force is zero on still charged particles. This means the particles that get stuck to the pieces of scale at the pipe are exposed to zero Lorentz force. Although the Lorentz force is much less than electrostatic force, the effect causes changes on the shape of the crystals from Calcite to Aragonite.

The Lorentz force on moving charged particles generate 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 causing a helical movement orthogonal to the fluid velocity. The wider the pipe, the higher is this orthogonal velocity. Hence the diameter of the pipe and the velocity of the charged particles have direct effect on the separation force. As the diameter of the pipe reduces due to deposition of mineral scale net Lorentz force would reduce and scale might deposit at a faster rate.

Aside from the effect of electromagnetic force in the presence of magnets, the effect remains for a while without magnets. When an external magnetic field is applied to a moving atomic or molecular dipole, they align themselves with the external field to oppose the repelling force. Even when the external field is removed, part of the alignment will be retained for a while. This effect is expected to play a role on the orientation of nascent $CaCO_3$ dipolar molecules during crystallization process helping linear orientation of the molecules. Once the crystals are formed and grew large enough to deposit, the rate at which they would stick to the pipe 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, and the scale flocks have week adherence tendency, they will be flushed out of the tube and less deposition will take place.

RESULTS AND DISCUSSION

Figure 1 represents scale build up and resulting pressure increase in initial flow studies (FS-1, FS-2 and FS-3). All these experiments were conducted in identical plastic tube of 3.3 mt length and 4 ml/min flow rate. FS-1 is the reference experiment without magnetic field, FS-2 and FS-3 are with 1 mt (30%) and 2 mt (60%) magnetic coverage respectively. The figure clearly shows the influence of magnetic flux on scale build up rate. In FS-1, flow pressure has shown three distinct phases. In the initial phase, up to 8 Hrs, there is no pressure build up, indicating no scale deposition or reduction of tube diameter. From 8 Hrs till 23 Hrs (slope A) pressure rose at a steady rate, indicating scale deposition and narrowing of tube opening. This phase was followed by rapid rise of flow pressure (slope-B) indicating complete chocking of tube. In case of FS-2, the initial phase is similar to FS-1, followed by a slow build up phase up to 25 psi (slope-C) and finally a rapid pressure rise indicating tube chocking. FS-3 with 60% magnetic coverage show impressive result with no pressure rise up to 68 Hrs. This phase was followed by a slow build up phase, indicating scale deposition (slope-F). However the pressure rise was limited to 30 psi only up to 130 Hrs of flow, which means scale deposition rate is reduced by a factor of 5. Comparison of initial pressure build up phase (slope-A, slope-C and slope-F) in three flow studies clearly indicate the effect of magnetic field on the crystallization and scale deposition process. Slope-A (without magnet) is sharper than slope-C (with 30% magnetic coverage), which is sharper than slope-F (with 60% magnetic coverage). Crystal morphology of deposited scales demonstrates the difference of crystal type under three flow studies. The scale crystals without magnetic field are purely calcite scale. The scale deposited in FS-2 is mixed aragonite (needle shape) and calcite scales whereas pure aragonite scale is obtained in FS-3 (Fig 4).

Flow pressure data represented Figure 2 are flow studies at different flow rates conducted in plastic tube with 60% magnetic coverage. The experiments were conducted at flow rate 4 ml/min (FS-3), 8 ml/min (FS-4) and 12 ml/min (FS-5). Two distinct phases could be seen in each flow study. The initial phase of very slow pressure build up was followed by a rapid buildup phase. Comparison of initial build up phases (slope- A, C & E) show that slope angle in FS-5 is least followed by FS-3 and FS-4. This supports the theory that at higher flow rate, Lorenz's force is highest which kept the ions separated. In case of FS-3 the ions are under magnetic field for the longest time which is possibly the reason of slow build up. In FS-4 the resident time and Lorenz's force are in the mid-range and thus the initial build up is faster. In the second phase of scale build up, the hysteresis is possibly the main acting force. The longer the exposure time under identical magnetic field, more hysteresis is expected. FS-5 having least residence time has least hysteresis followed by FS-4 and FS-3. This hypothesis is supported by highest slope angle for FS-5 followed by FS-4 and FS-3. However due to higher flow rate (kinetic force) of FS-4 compared to FS-3 the scale flocks are more efficiently flushed out in FS-4 and thus ultimate pressure build up in the given experimental period is least compared to FS-3 and FS-5.

Figure 3, which represent the flow studies conducted in copper tube; show a sharp pressure rise at the initial phase. FS-6 (4 ml/min) is the first to show pressure rise followed by FS-8 (12 ml/min) and FS-7 (8 ml/min). In the final phase FS-7 shows best result and the pressure increased only up to 12 psi for a long flow period (190 Hrs).

The results show that magnetic force has direct effect on scaling reduction on the explained tests. The effect comes as the result of Lorentz force on moving charged particles. The force not only repels differently charged ions, but also causes slight deformation on bipolar shape. The deformation changes the type of crystals from calcite to aragonite and therefore reduces the adhesiveness of the crystals. The authors claim that the Lorenz force repels the positive and negative sides of the bipoles and causes some deformation on its shape. The Lorentz force causes instability in dipoles lattice formation by enforcing stress on dipolar walls. When the deformation gradients into a critical point the attraction force of opposite charges completely equals the shear stress exerted by the mechanical force of the fluid pump. This phenomenon can happen only on certain concentric cylinder of the fluid with the critical velocity and therefore slows down the crystallization process. As a result the scaling process slows down and the rate of reduction of the effective diameter of the pipe reduces drastically. This has been observed in figures 1-3.

The pressure inside the pipe is a function of the fluid density, flow rate, pipe's diameter, friction, length of the pipe and viscosity losses. The change in fluid pressure is reciprocal to the square of the cross-sectional area. This change can be explained better by determination of Reynolds Number:

$$R_e = \frac{wD}{v}$$

$$\begin{cases} R_e = ReynoldsNumber \\ w = VelocityofFlow \\ v = KinematicViscosity \\ D = EffectiveDiameterofPipe \end{cases}$$

Values less than 2320 for Reynolds number causes laminar flow, which can be modeled as a series of moving concentric cylinders of the fluid. The most inner cylinder has the maximum velocity while the most outer cylinder that is adjacent to the pipe's wall has the minimum velocity. The friction between the layers of moving cylinders slows down the movement of each other. The outer cylinders have bigger surface and thus bigger friction down to the last layer that has contact with the pipe's wall. As it is explained before, the Lorentz force is proportional to the velocity of the moving charged particles and thus the force descends to the least at the pipe's wall. According to our claim of the direct effect of Lorentz force on scaling reduction, it is concluded that the scaling ascends as the velocity descends at the pipe's wall. It then takes some time before the whole inner wall of the pipe gets covered by a thin molecular size layer of scale with not much effect on the effective diameter. The relation between the change in pipe's pressure and its diameter can be derived as follows:

$\lambda = \frac{64}{R_e}$ Friction Coefficient at laminar flow

$$\Delta P = \frac{\rho w^2}{2}\left(\lambda \frac{L}{D} + \sum \zeta\right)$$

$$w = \frac{Q}{\pi r^2} = \frac{4Q}{\pi D^2}$$

$$\Delta P = \frac{8\rho Q^2}{\pi^2 D^4}\left(\lambda \frac{L}{D} + \sum \zeta\right)$$

The above equation shows how the pressure changes as a function of other parameters in the pipe.

$$\begin{cases} \Delta P = PressureChange \\ P = Pressure \\ \rho = Density \\ Q = VolumetericFlowRate \\ D = EffectiveDiameterofPipe \\ \lambda = FrictionCoefficient \\ L = LengthofPipe \\ \zeta = ViscosityLossesduetotheroughnessofthepipe \end{cases}$$

That means a very small change in the pipe's diameter has a significant effect on the pressure.

The other important observation revealed by this study is that the magnetic effect is stronger in copper tube than plastic one. It is seen from magnetic flux measurement that flux density is slightly higher in copper than plastic pipes, which may be one of the causes. In addition, the copper tube reduced the electrostatic attraction of oppositely charged particles by conducting the free electrons. It also shows that magnetic flux density inside copper tube is higher than plastic tube by a factor close to the predicted reduction factor and the flux decays to nil at a distance 12 cm in both cases.

The delay in scale formation, deposition and pipe 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. It is also evident from this study that length of magnetic coverage and thus the time during which the fluid is exposed to the magnetic field is important for scale inhibition process.

CONCLUSIONS

From this study the following conclusion could be made-

1. Scale deposition rate is slowed down due presence of magnetic field. The process of slowing down is attributed to the Lorentz force which is the main motive that prolongs the scaling process
2. Scale deposition rate is dependent on magnetic coverage area and residence time of scaling ion within the field.
3. Magnetic effect is found to be stronger in copper tube than plastic tube which is due to higher magnetic flux in copper tube than plastic pipes.
4. Optimization of magnetic coverage area or resident time under magnetic field along with optimum fluid velocity is essential for scale prevention.

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