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# Prediction of the calcium carbonate growth rate in a vertical slot due to the effect of pressure drop

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## Abstract

A slotted liner is widely used in steam assisted gravity drainage (SAGD) of heavy oil due to its low cost of production and ability to retain the majority of the sand in the oil reservoir. A pressure drop occurs as the oil-water mixture passes through the very narrow rectangular slot leading to the precipitation of calcium carbonate and ultimately the plugging of the slots. The goal of this study is to observe the locations where scaling occurs and predict the growth rate of calcium carbonate in the slot. To undertake this, two experimental measurements are needed, a determination of the pressure field from the velocity data and monitoring the growth of the calcium carbonate. The results show that the velocity increases as the supersaturated flow with scaling ions enters the slot with a subsequent decrease in pressure. Highest pressure drop occurs at the slot entrance due to sudden changes in the geometry. The resulting pressure drop causes the build-up and growth of calcium carbonate. This growth further reduces the pressure which in turn leads to subsequent growth of calcium carbonate, and this phenomenon continues in a cyclic way until the plugging of the slot. Most of the studies in the literature undertaken so far have been based on the effect of thermodynamic parameters such as pH, temperature and saturation ratios on the calcium carbonate precipitation and crystal growth. However, this study will help to understand the effect of pressure drop caused by the sudden geometry contraction and flow convergence on the calcium carbonate build-up and the growth.

## 1 Introduction

Calcium carbonate formation, also known as scaling, is the main component of scale encountered in different major industries such as desalination, oil and gas, geothermal energy and steam power plants (Cowan et al. 1976, Muryanto et al. 2012). Scaling is the deposition of salts on industrial equipment and causes deleterious effects such as the reduction of pipe diameter and increased wall roughness leading to increased flow friction and pump power consumption as well as diminished heat transfer efficiency through low thermal conductivity (Cowan et al. 1976). Understanding the formation of scaling requires knowledge of the chemistry of scale formation of the specific salt as well as the flow conditions that will be unique to a specific geometry industrial component.

In the oil and gas industry, SAGD is a proven technology to produce bitumen from oil reservoir (Cheung et al. 2013). For this technology, two horizontal pipes are drilled up to 400 m below surface and extend up to 1km horizontally underground. They are vertically parallel to each other with a spacing of 5 to 10 meters in between them. During production, high temperature steam is injected into the upper well which reduces the viscosity of bitumen by several orders of magnitude and flows into the lower well under the influence of gravity (Banerjee et al. 2013). A slotted liner design is an economical method to minimise sand production during oil extraction. This is a casing tube that has thousands of narrow, axially oriented slots that are sized for the particular particle size distribution of the unconsolidated formation sand of the reservoir. When the oil-water mixture penetrates these narrow rectangular slots, the flow converges due to the sudden contraction of the geometry. Observations have shown that there is precipitation of calcium carbonate within the slots that ultimately leads to plugging of the slots (Erno et al. 1991), one of the important failure mechanisms in the system.

In a prior work, surface scale formation has been studied for a flow across a stainless steel capillary tube and semi-annular coupons (Bello et al. 2017, Muryanto et al. 2012). The results show that the calcium carbonate scale formation increases with increase in flow rate and hence pressure drop, saturation ratios and temperature. The effect of surface energy and roughness has been also widely studied (Cheong et al. 2013). These properties significantly aid in the growth of calcium carbonate on the substrates considered. Also, the effect of the pH and solution chemistry is studied on the bulk precipitation of calcium carbonate (Andritsos et al. 2003, Frota et al. 2013). It was seen that increase in pH and rate of scaling ions increase the deposition of the calcium carbonate.

The near-well bore fluid mechanics where the fluid flow converges the slot has been previously studied using a semi-empirical method (Kaiser et al. 2002). Based on this method the relationship between the slot density and pressure drop was established. Flow convergence in rectangular slots using particle shadow velocimetry was studied by Yusuf et al. (2018). This study concluded that flow convergence due to geometry contraction causes a significant pressure drop in the near slot entrance region. Also, a relationship was established to show that pressure drop increases with increase in the curvature of streamlines as the Reynold's number increases.

In this study, an experimental set-up was developed to simulate the flow to observe the precipitation of calcium carbonate into a narrow slot. The goal of this study is to observe where scaling occurs and to predict the growth rate of calcium carbonate in the slot. Determination of the velocity field in the near slot entrance region is also investigated for the clean slot as well as with the onset of scaling to observe precipitation characteristics related to the flow. To undertake this, two experimental measurements are needed, a determination of the pressure field from the velocity data and monitoring the growth of the calcium carbonate.

# 2 Theory

## 2.1 The chemistry of calcium carbonate scale formation

The scaling phenomenon can be affected by the local pressure field as the pressure is reduced after the fluid flow enters a confining geometry. However, the major driving force behind the calcium carbonate scale formation is the supersaturation level of the oil-water mixture in terms of calcium ($Ca^{2+}$) and bicarbonate ($HCO_3^-$) ions (Cheung et al. 2013). So, the pressure drop acts as a catalyst in this process and changes the bicarbonate-carbonate equilibrium towards the carbonate equilibrium leading to calcium carbonate precipitation as given by:

$$\mathrm{Ca^{2+}_{(aq)}} + 2\mathrm{HCO^{-}_{3(aq)}} \leftrightarrow \mathrm{CaCO_{3(s)}} + \mathrm{CO_{2(s)}} + \mathrm{H_2O_{(l)}} \tag{1}$$

The possibility of calcium carbonate scale formation is determined by the calculation of supersaturation ratio (SR). This ratio is defined as the ratio of concentration of calcium ($Ca^{2+}$) and carbonate ($CO_3^{2-}$) ions to the solubility product constant ($K_{sp}$) of the calcium carbonate as given by (Bello et al 2017):

$$\mathrm{SR}=\frac{[\mathrm{Ca}^{2+}][\mathrm{CO}_3^{2-}]}{\mathrm{K}_{\mathrm{sp}}} \tag{2}$$

If the SR is lower than 1 the solution is under saturated and no precipitation will occur. When the SR is equal to 1 the solution is saturated and the rate of precipitation and dissolution are same. Whereas when the SR exceeds 1 the solution is supersaturated and creates ideal scenario to form calcium carbonate scale under secondary conditions such as reduction in pressure or increase in temperature.

## 2.2 Pressure drop

As the fluid flow enters the narrow rectangular slot it experiences a sudden change in the geometry and cannot adjust itself which results in flow convergence as shown in Figure 1. As the flow converges the curvature in streamlines increases with increase in fluid velocity and accompanying reduction in pressure (Yusuf et al. 2018).

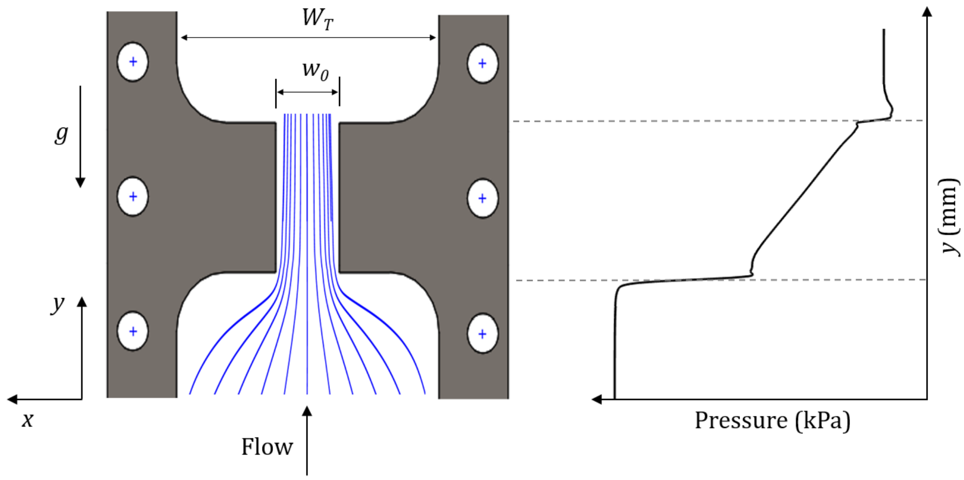



Figure 1: Flow convergence and associated pressure profile (representative) through the sudden geometry contraction of a narrow slot

The head loss as the flow passes through the slot is strong function of geometry profile as well as the fluid velocity and its properties. The Bernoulli's equation can be used to discuss the loss in static pressure to the gain in the velocity head when the fluid encounters the sudden geometry contraction, and the associated pressure loss coefficient is given by:

$$K=\frac{\left(\frac{\Delta P}{\rho g}+\Delta Z\right)}{\left(\frac{V^2}{2g}\right)} \tag{3}$$

where $\Delta P$ is the differential pressure across the slot with $\Delta Z$ as the elevation head, $V$ is the average velocity through the slot for a fluid flow with density $\rho$.

Pressure drop for a flow through the rectangular orifice has been previously studied for different aspect ratios ($AR$). Experimental measurements showed that pressure drop increased with an increase in the aspect ratio (Yusuf et al. 2017). A model was established to develop a relationship between the pressure drop and aspect ratio. Flow convergence parameter ($\Phi$) is taken into consideration to develop this model which describes the converging behavior of the flow. The pressure loss model is given by:

$$K = \frac{\Delta P}{\frac{1}{2}\rho u^2} = (1 - \alpha^2) + (1 - \alpha)\left[\frac{2AR}{AR + 1}\right]\left[\frac{4\Phi}{\sqrt{\pi}.Re}\right] \quad (4)$$

where $u$ is the average velocity through the orifice. The area ratio, $\alpha$ characterizes the confining conditions in the far while the aspect ratio, $AR$ characterizes the rectangular geometry of the slots, an important design parameter. These are defined as:

$$\alpha = \frac{w_0}{w_T} \quad (5)$$

$$AR = \frac{d}{w_0} \quad (6)$$

where $w_0$ is the slow width, $w_T$ is the width of the open area, $d$ is the length (depth in Figure 1) of the slot.

# 3 Experimental set-up

An experimental set-up, shown in Figure 2, was used to determine the pressure field as well as to monitor the growth of calcium carbonate and measure the velocity field. This consists of a high-speed camera (either a SP-5000M-PMCL-CX; JAI Inc. for image of calcium carbonate growth or a FASTCAM Mini WX50; Photron Inc. for collecting PIV images) coupled with 105mm lens (f2.8-DG Macro; EX SIGMA Inc.) and extension tubes, an LED light source (Pulsar 320; Advanced illumination Inc./ILA.LPS 3, ILA5150 GMbH, Germany), flow cell, peristaltic pump (Masterflex L/S; Cole-Parmer Inc.), magnetic stirrer and the pressure transducer (DP15-36; Validyne Inc.). The function generator (AFG3021B; Tektronix Inc.) was used to control the frame rate of the camera being used.

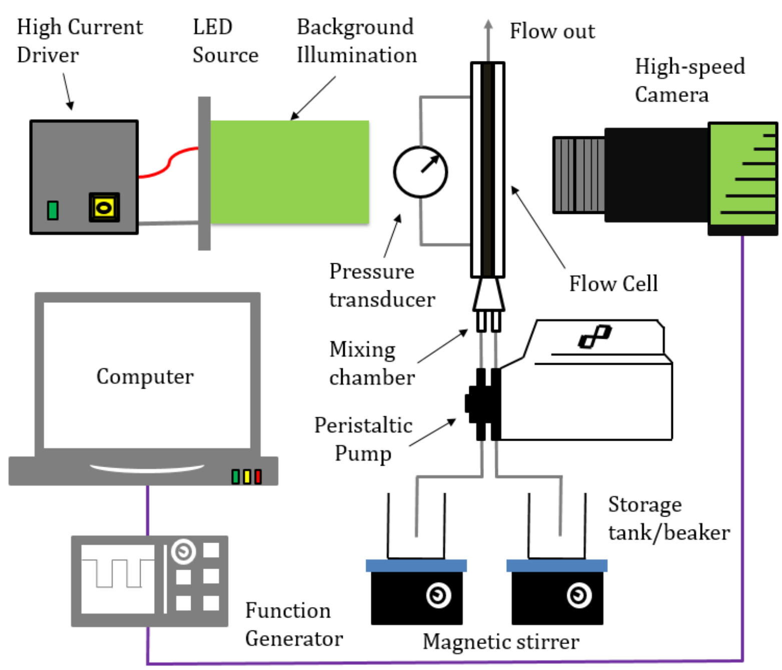
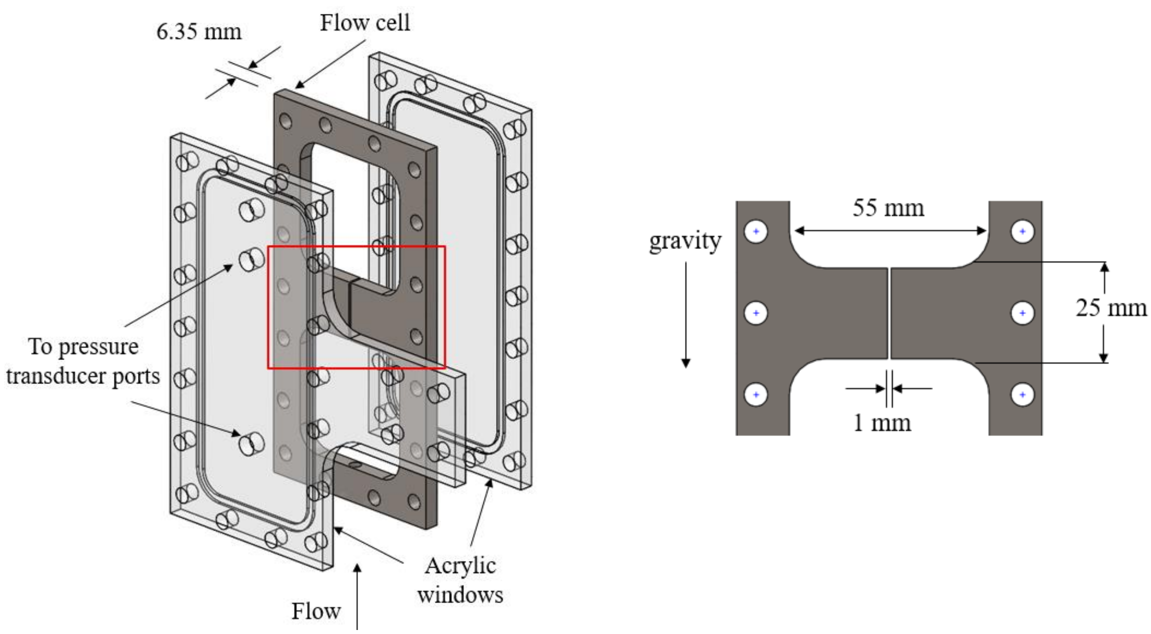



Figure 2: A schematic of the experimental system used for both imaging the velocity field and measuring pressure drop across the slot.

The flow cell shown in Figure 3(a) is sandwiched between two acrylic sheets to allow for the transparency and visualize the desired phenomenon. A thin layer of Teflon (23-5S-3D; CS Hyde Inc. USA) with thickness 0.13mm installed adjacent to the acrylic sheets to reduce the nucleation rate of calcium carbonate (Wang et al. 2005). This ensures that the calcium carbonate scale grows on the two sides of the stainless steel walls and not effectively on the acrylic sheets in front of the camera, and allows the capture the images with best possible clarity. The flow cell has a thickness of 6.35 mm and is made of stainless steel (AISI 316). The rectangular slot geometry is full plate thickness with a width 1 mm and length 25 mm as shown in Figure 3(b). A pressure transducer was located across the slot to measure the static pressure drop as the flow passes through the geometry with the sudden contraction. All experiments were performed at room temperature (20° C).




(a) (b)

Figure 3: Schematics of the (a) complete flow cell and (b) details of the slot geometry.

In the first experimental study, fluid was passed through the slot to measure the velocity of the flow field on the channel centerline. Particle shadow velocimetry (PSV) was used to measure the two dimensional velocity field and from this, determine the pressure field. Tracer particles of 20 µm diameter hollow glass spheres (Dynoseeds TS20, Microbeads) were added into the water. These casted a shadow onto the high speed camera (FASTCAM Mini WX50; Photron Inc.) from the background light source (ILA.LPS 3, ILA5150 GMbH, Germany). The experiment was undertaken at a flow rate of 1200 ml/hr and images were captured during the experiment at 2000 fps. Particle image velocimetry (PIV) processing was used to obtain the velocity field using the multi-pass sum-of-correlation algorithm (DaVis 8.4, LaVision GmbH) with a decreasing interrogation window size (64×64 to 32×32 pixels with 87% overlap). This velocity field was further used to determine the pressure field using the Poisson's equation, which correlates the velocity field with the second derivate of pressure (Ansari et al. 2018).

For the scale build up experiments, an aqueous solution saturated with calcium chloride (C79-500; Fisher Chemical Inc.) and sodium carbonate (S263-500; Fisher Chemical Inc.) was separately pumped at the flow rate of 600 ml/hr using a peristaltic pump. These separate flows were mixed in a chamber just before the combined flow enters the flow cell. The concentration of calcium and sodium carbonate considered in the experiment was 0.01M. As per the stoichiometric calculations performed in an available software (Visual MINTEQ V3; KTH Sweden, Gustafsson et al. 2010) the aqueous solution would be supersaturated which is a suitable condition to form the calcium carbonate scale. The aqueous solution of the calcium chloride and sodium carbonate passed through the same vertical flow cell in a single pass and discharged to effluent. A CMOS high-speed camera (SP-5000M-PMCL-CX; JAI Inc.) with a background light source (Pulsar 320; Advanced illumination Inc.) was used to visualize the continuous growth of calcium carbonate. The camera captured the images every 5 minutes to monitor its growth in the slot over the 4-5 hours of the experimental time. Simultaneously the reduction in pressure caused by the subsequent growth of calcium carbonate was measured with the pressure transducer across the slot.

The images captured every 5 minutes during the scaling experiment were processed using custom code (Matlab 2017a, MathWorks Inc.) to determine the change in the width of the slot over the period of time. As an example the raw image collected was processed using the Otsu's method to create a binary image with a threshold of 0.375 as shown in Figure 4. The width of the slot along its length was determined. It was assumed that the scale is only building up on the sidewalls of the slot made from the stainless steel plate. The purpose of the Teflon shim material adjacent the acrylic windows was to prevent scaling forming on the windows. With this assumption, a change in the cross-sectional area of the slot can be calculated based on the width change due to scaling. This can be used to calculate also aspect ratio, $AR$ as defined in equation 6.

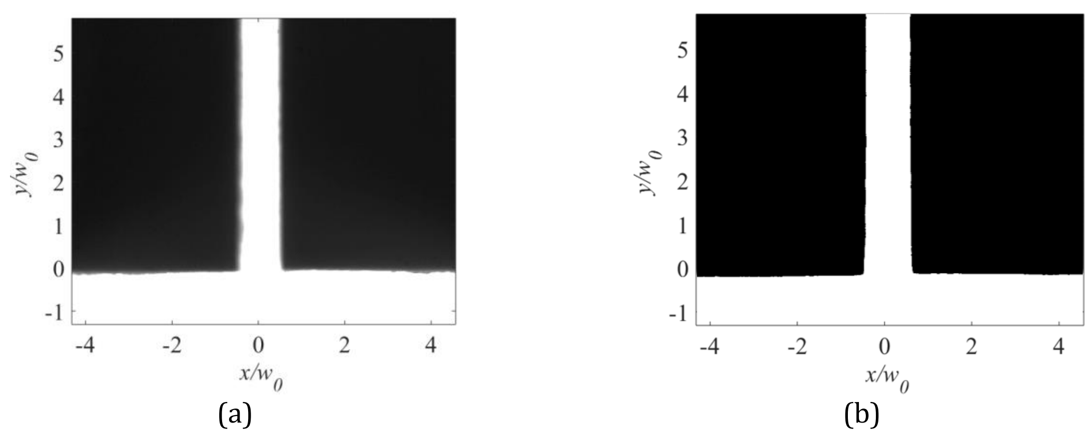
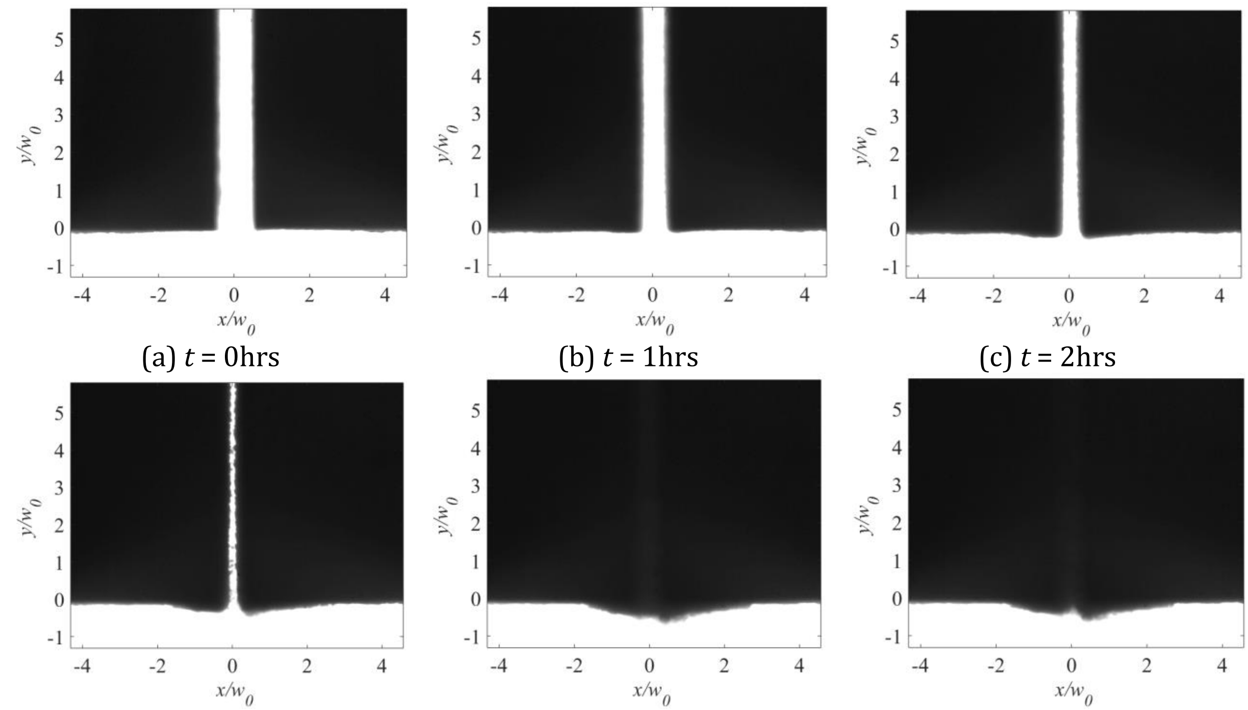



Figure 4. Images of the entrance region of the slot from (a) the raw camera image at the start of the experiment at $t$ = 0hrs and (b) after binarizing the image.

# 3 Results

As the flow enters the flow cell, it passes through the slot and leads to reduction in pressure. The supersaturated fluid flow with scaling ions and pressure drop causes the formation and growth of calcium carbonate with time as shown in Figure 5(a)-(f). The Teflon on acrylic windows is effective to reduce the calcium carbonate nucleation rate, and hence the growth mainly occurs on stainless steel side walls.

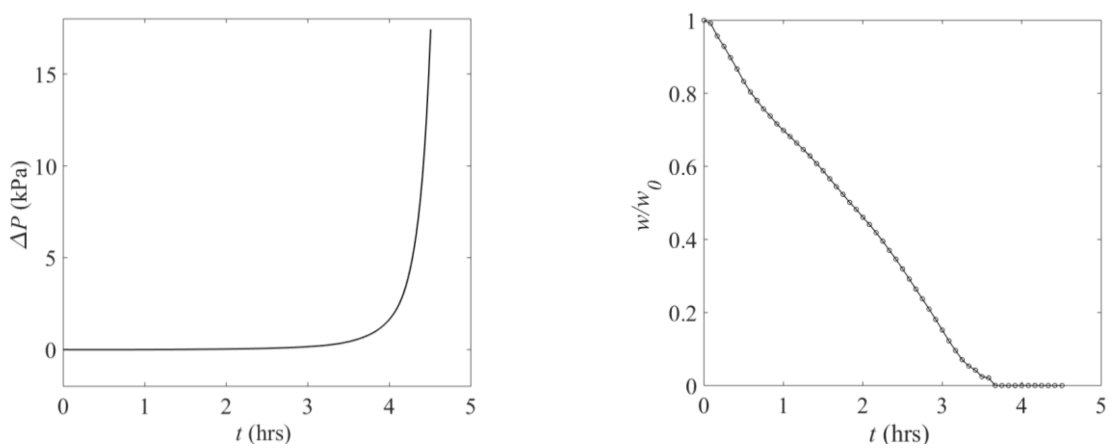



(a) $t$ = 0hrs (b) $t$ = 1hrs (c) $t$ = 2hrs

(d) $t$ = 3hrs (e) $t$ = 4hrs (f) $t$ = 4.6hrs

Figure 5. Shadow images of the calcium carbonate growth in the slot, (a-f) at intervals in the experiment.

As a result of the calcium carbonate growth the pressure drop across the slot starts to increase with time and asymptotically reaches to maximum when the slot is completely plugged as shown in Figure 6 (a). The reduction in the slot width as function of time is plotted in Figure 6 (b) and shows the slot width approaches zero and becomes plugged at $t \sim 4$ hrs. The slope of the reduction in slot width can considered to be the rate at which the calcium carbonate grows within the slot. The estimated growth rate from Figure 6 (b) is 0.19 mm/hr and is almost linear in nature for the straight slot geometry.




(a) (b)

Figure 6. (a) The time history pressure trace (b) Change in the slot width with time due to calcium carbonate growth. $w_0$, and $w$, are the original and current slot width respectively.

The reduction in slot width leads to an increase in the aspect ratio of the slot as defined by Equation 6. It can be seen from Figure 7(a) that as the measured aspect ratio, $AR$ increases, the pressure drop increases. The increase in velocity due to a lower width reduction is balanced with corresponding reduction in the pressure. However, the pressure loss coefficient, $K$ plotted in Figure 7(b) shows asymptotic behavior with increase in the $AR$. This is because the pressure loss coefficient is dominated by the square of the average velocity in the slot in comparison to the aspect ratio. Based on Equation 4, it can concluded that flow is converging as the pressure loss coefficient decreases with increase in $AR$. As the curvature of the streamlines increases, pressure drop increases which is seen in Figure 7. These results are consistent with the earlier studies conducted (Yusuf et al .2017 and 2018).

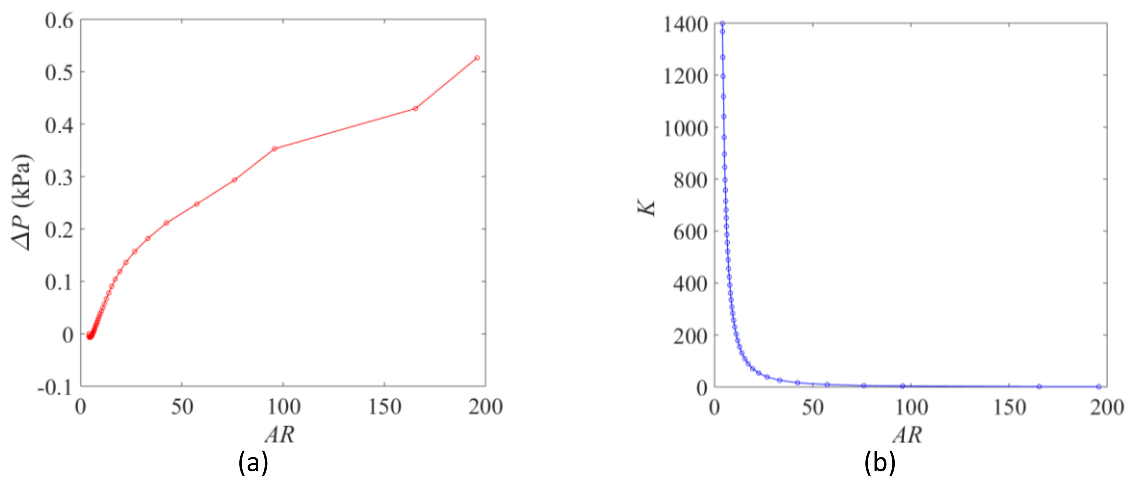



Figure 7. Pressure loss coefficient ($K$) and Pressure drop ($\Delta P$) vs Aspect ratio ($AR$)

The 2D-velocity and pressure field were obtained from the particle shadow velocimetry experiments as shown in Figure 8. The results show that velocity increases in the slot with subsequent reduction in the pressure. It can been seen that the highest change in pressure occurs at the entrance of the slot as the fluid cannot adjust itself and converges due to the sudden changes in the geometry. Figure 8 (c)-(d) show the 2D-velocity and pressure field for the calcium carbonate growth at time 2hrs. This growth further causes the streamlines to converge significantly and leads to the increase in the velocity and subsequent pressure drop in comparison to the results at time 0hrs.

Based on the results from Figure 5, it can be seen that the calcium carbonate growth occurs in and around the slot region, which is a low pressure region as confirmed in Figure 8 (b). Also, this growth subsequently affects the flow and further leads to flow convergence shown in the velocity field in Figure 8(c) and hence the subsequent decrease in the pressure Figure 8 (d). Based on these results it can be said that this cycle of calcium carbonate growth and increased change in local pressure continues till the slot becomes plugged.

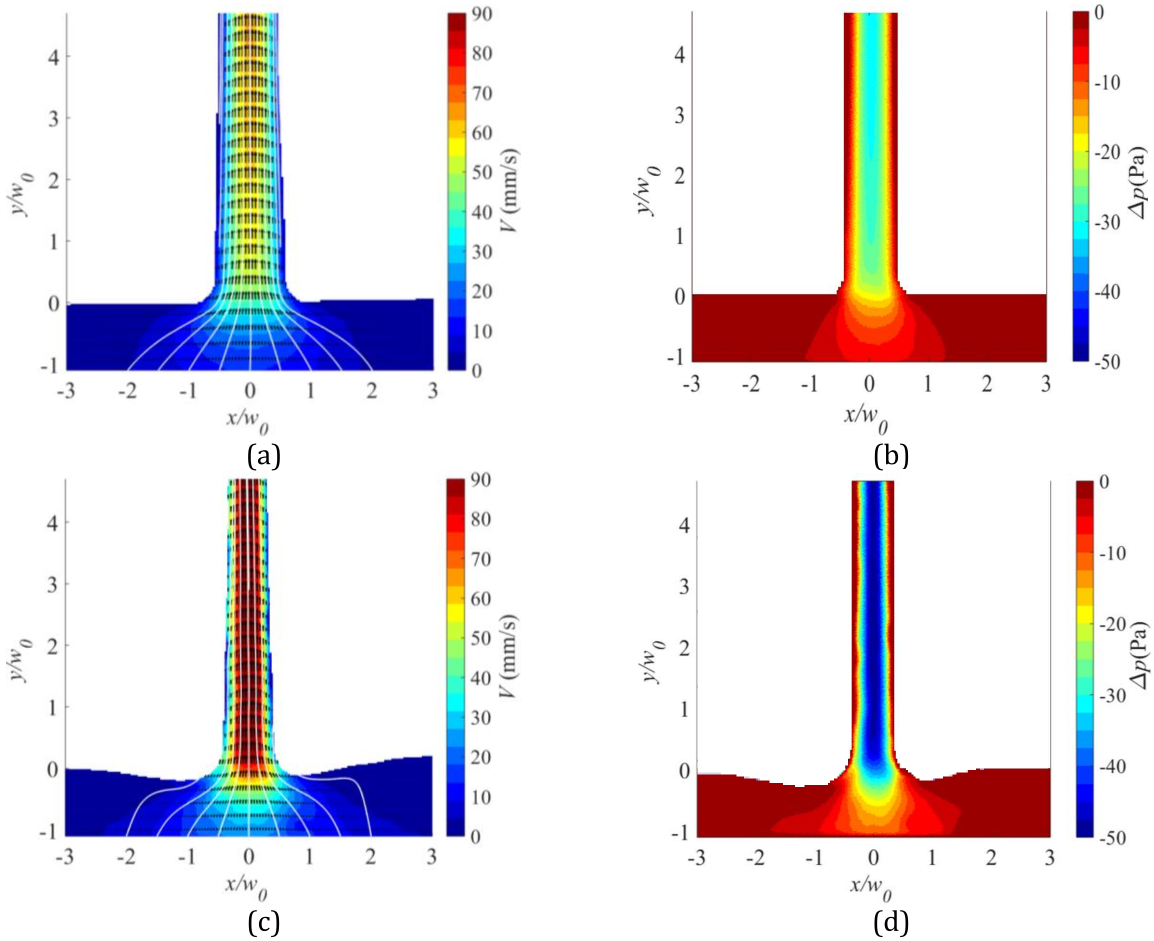



Figure 8. Results for (a) and (b) 2D-velocity and pressure field at $t$ = 0hrs respectively (c) and (d) 2D-velocity and pressure field at $t$ = 2hrs respectively

# 4 Conclusion

This study has provided insights to understand the effect of a change in local pressure on the growth of calcium carbonate in the geometry with sudden contraction using the PSV and scale build-up experiments. It confirms that when the supersaturated flow enters the strong convergence region of a slot, calcium carbonate precipitates and growth occurs in and around the low pressure entrance region due to the sudden reduction in pressure. With the subsequent growth of calcium carbonate, the aspect ratio, $AR$ increases and leads to a stronger flow convergence as well as an increase in the curvature of streamlines with a subsequent stronger reduction in pressure. This cycle of calcium carbonate growth and pressure drop continues until the slot plugs.

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