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EXPERIMENTAL STUDY OF LIQUID-SOLID FLOW APPLIED TO LOST CIRCULATION CONTROL IN FRACTURED CHANNEL

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Abstract. *In this work the process of filling fractures through the injection of solid particles into a flow is investigated experimentally. The experimental set-up comprises a rectangular test section with a transverse fracture, instrumented with pressure gauges, flow and temperature monitors. In order to characterize the fracture filling pattern, the influence of variations of the fracture thickness (16, 20 and 26 mm), the fracture outlet initial flow rate (from 0.25 to 1.25) and the Reynolds number (150, 300 and 450) along the position, length and height of the formed bed of particles is investigated. The particulate flow is represented by a solution of water-glycerin with abrasive plastic - Urea particles. Results show that all the parameters present the ability to modify the geometric characteristics of the bed, having a direct influence on the filling time and the fluid lost by the fracture.*

Keywords: *liquid-solid flow, fractured channel, lost circulation, experimental set*

1. INTRODUCTION

The high costs and the increasing complexity of processes associated with the oil exploration and production have required numerous studies focusing on problems concerning the well drilling. The solutions found in these studies seek to minimize the use of remedial jobs and the non-productive time (NPT) during drilling (Kumar and Savari, 2011). The drilling is performed by the rotational movement of a drill that compresses and grinds the rock, generating a lot of gravels. The outcoming cuttings are removed continuously due to the drilling fluids which is injected into the drill column and returns to the surface through the annulus region between the substrate walls and the drilling column (Azar and Samuel, 2007).

The drilling fluid density is the main source of the well hydrostatic pressure. Its contribution to the well pressure can be expressed in terms of the equivalent circulating density (ECD) which must be inserted within a safe operation range, contained between the pore pressure and the breakdown pressure in the formation (Cook *et al*., 2012). Figure 1 illustrates the safe window and also the lower and the upper limits that characterize uncontrolled fluid influx and severe fluid losses, respectively. The experimental study presented here is restricted to the lost circulation problem in fractured formation which is commonly observed in drilling operations. The ECD range covered in this study includes safe and severe fluid losses conditions.

The fractures generation results from failures, which occurs when the tension exerted on the formation exceeds the circumferential tension around the well and the rock tractive force, usualy due to the high pressure gradients associated to the process. As a result the fluid invasion towards the formation will occur as the porous substrate gets fractured. Therefore, a phenomenon rather undesirable for the oil industry, so called lost circulation, takes place (Almagro *et al*., 2014; Calçada *et al*., 2015).

The lost circulation is defined as the drilling fluid that flows towards the rock formation through the pores or cracks in the well-formation set. This phenomenon, which is aggravated since a preferential flow is verified if the formation is fractured, can compromise the operation of the well (Almagro *et al*., 2014). Among all the different ways to control such phenomenon, the process of injecting solid particles with the drilling fluid to seal the fractures has been the focus of plenty of studies in the last decade. Such method consists of adding particulate material with selected granulometry, namely Lost Circulation Materials (LCM), to the drilling fluid (Whitfill and Hemphill, 2004; Suyan *et al*., 2007).

Therefore, the objective of this work is to present an experimental apparatus to analyze the addition of particulate material to the fluid injection process in order to fill the fracture through the particles deposition. Results show the influence of variations on the fracture thickness, the fracture outlet initial flow rate and the Reynolds number over the fracture filling process. In this study, parameters such as the length, the final height and the starting position of the formed bed as well as the time required to observe partial or total sealing of the fracture are monitored.

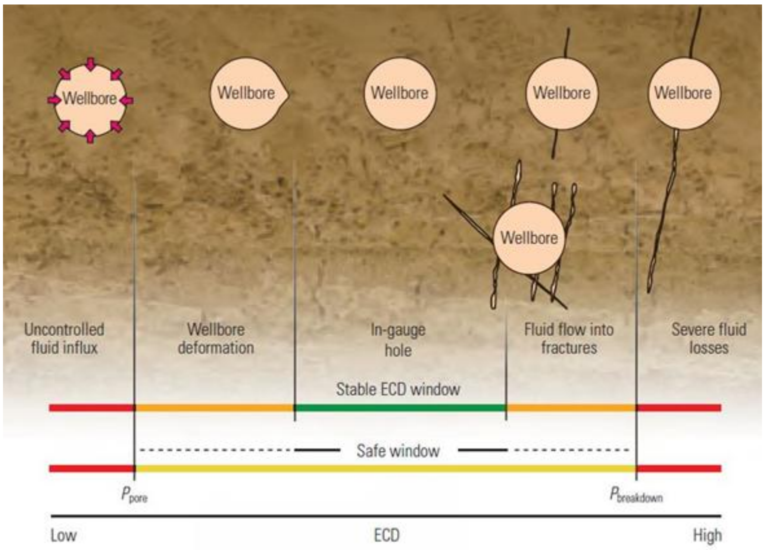

Figure 1: Operating range and well profile according to the ECD of the drilling fluid.
(Adapted from Cook *et al.*, 2012)

2. PROBLEM FORMULATION

Operations in the oil and gas industry have a high complexity of parameters commonly associated to geometry and operating conditions. In order to make the analysis possible some assumptions, presented in Figure 2(a), must to be done. A vertical channel (representing the oil well) with a single fracture in a horizontal plane is considered; the geometry is symmetrical about the center of the drill column. As displayed in Figure 2(b), the fluid flow inside the column is not the focus of this work, as the goal is to observe the particle transport in the annulus and the particle deposition inside the fracture. Moreover, such assumption refers to the formation adjacent to the well, which is considered as impermeable.

The Figure 2(c) shows the region of interest for the study, in which the fracture is represented by its length, h_{FR}, and thickness, e_{FR}. With regards to the vertical channel, the length upstream and downstream the fracture are represented by l_{UP} and l_{DW}, respectively. Therefore the fluid loss control occurs as the particulate material is injected with the drilling fluid, in order to obtain the fracture filling along the time.

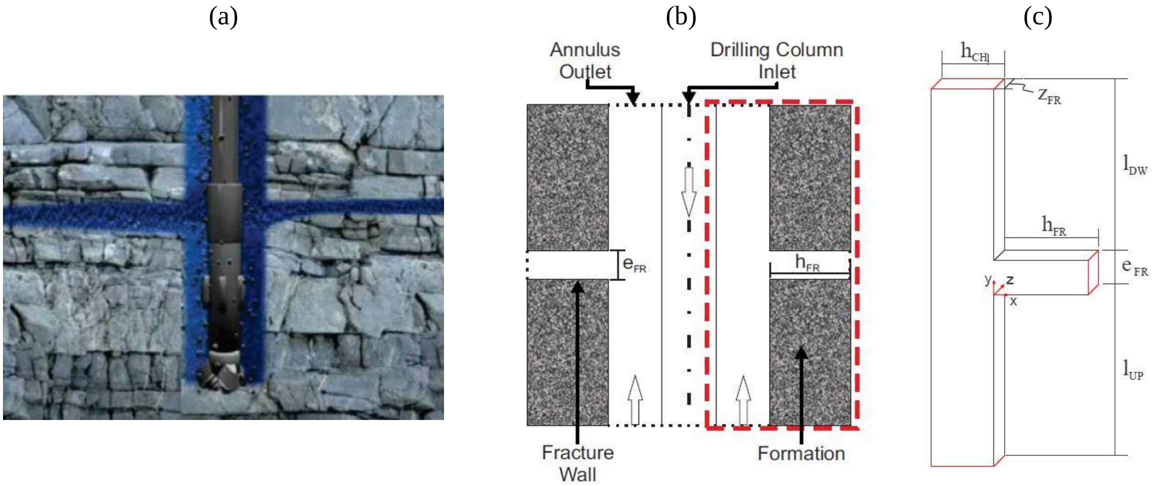

Figure 2: Simplifications: (a) well-fracture set; (b) idealization and (c) region of interest.
(Adapted from Barbosa *et al.*, 2016)

3. MATERIAL AND METHOD

The tests were performed in an experimental set designed and built to characterize the particle flow and the bed of particles formation along the fracture. Figure 3(a) shows the hydraulic circuit diagram and Figure 3(b) shows the key components of the experimental set installed on the Porous Media Lab dependencies (LaMP) at the Research Center for Rheology and Non-Newtonian Fluids (CERNN – UTFPR).

(a) (b)

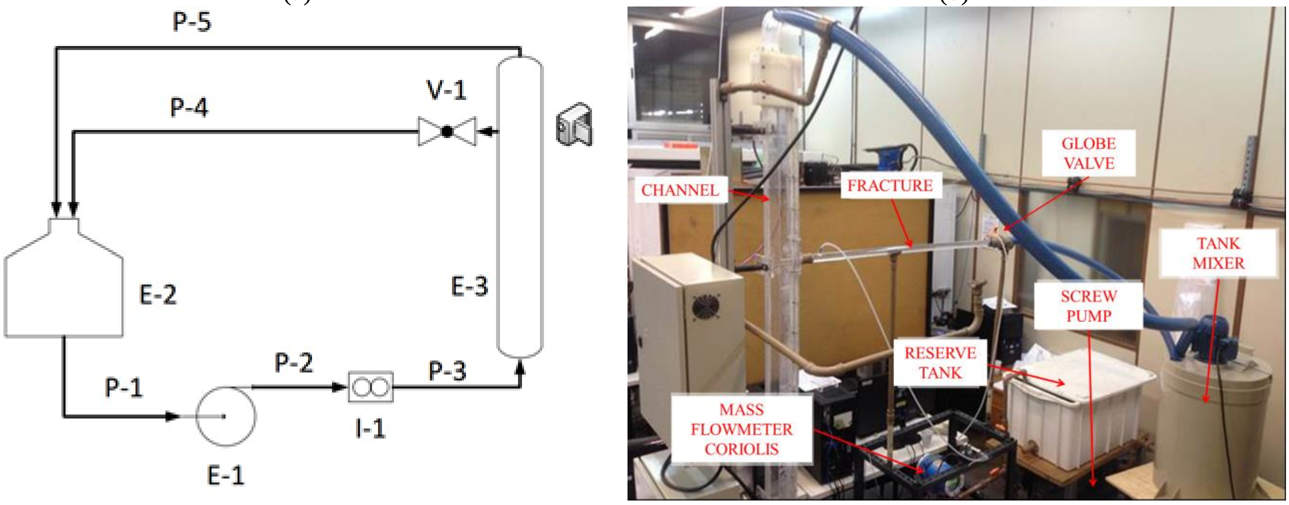

Figure 3: Experimental set: (a) hydraulic circuit diagram and (b) overview of the key components.

The experimental set consists of a tank with mixer (E-2) to homogenize the liquid-solid solution, in which there is a J type thermocouple to measure the solution temperature during the tests. A screw pump (E-1) provides the flow through the entire circuit. After leaving the pump the solution passes through a Coriolis type mass flowmeter (I-1) designed to measure the mass flow rate in real time before reaching the test section (E-3). The test section present two exits (one at the upper nozzle and another at the end of the fracture); the fluid is redirected to the tank via two hoses (P-4 and P-5) which have larger diameters than the outlets, so that the pressures are atmospheric.

The test section is made of acrylic to allow the capturing not only of the flow images but also of the particles bed formed along the fracture. The test section, designed to represent the well annulus region, has a rectangular cross section of 45x16mm and 2m long. The fracture is located 1.28m from the vertical channel inlet to ensure a fully developed flow. The channel width represents the dimension of the annular region, for a well opening with outer and inner diameter, of 8.5 and 5 inches, respectively. Such dimensions are based on a given step of the drilling process, as suggested by De Lai *et al*., 2015 and Calçada *et al*., 2015. In order to measure the local pressure, the section has two relative pressure transducers: one (I-3) located 0.23m from the channel inlet and the other (I-2) located near the channel outlet (1.77m) above the fracture. Figure 4 shows the transmitters position and the test section dimensions.

A solution containing 68.9% of glycerin mass concentration in water, with density (ρ_g) of 1.175 g/cm³ and dynamic viscosity (μ_g) of 16.912×10^{-3} Pa.s at 25ºC, was used during the tests. Particles of abrasive plastic (Urea), displayed in Figure 5, with density of 1.5 g/cm³ and diameters between 0.8 and 1.2 mm, were added to the solution to obtain 3% mass concentration of particulate material. The resulting fluid to particulate mass ratio is about 1.28.

Tubes of 1m long with different diameters (16, 20 and 26 mm), displayed in Figure 6(a), were employed to characterize the fracture thickness (e_{FR}) influence. To investigate the effects of the fracture outlet initial flow rate (Q_V), the experimental set up was equipped with a globe valve (V-1) positioned at the fracture end, as shown Figure 6(b). During tests the valve is opened in ¼ turns, i.e., Q_V = 0.25 at each time. Also, to observe the influence of channel flow speed in the fracture filling, different values of the vertical channel Reynolds number (Re), defined in Eq. 1, (150, 300 and 450) were evaluated for the same fracture thickness (e_{FR}) and valve opening (Q_V).

$$\mathrm{Re} = \frac{\rho_g \bar{V} D_H}{\mu_g} \tag{1}$$

where $\bar{V}$ and D_H are respectively, the average flow velocity in the vertical channel inlet and the channel hydraulic diameter.

To perform the tests it is necessary to keep the mixing tank (E-2) working for five minutes to homogenize the solution before the screw pump (E-1) be started by a frequency inverter. Thus, the flow starts to pass through the vertical channel as the fracture end valve (V-1) is kept closed. As the homogenized particulate flow is visually verified along the test section, the fracture valve is opened, allowing the fluid to flow at the desired initial flow rate. Measurements and the fracture filming to capture the bed formation are started moments before the opening of the fracture valve.

(a)

(b)

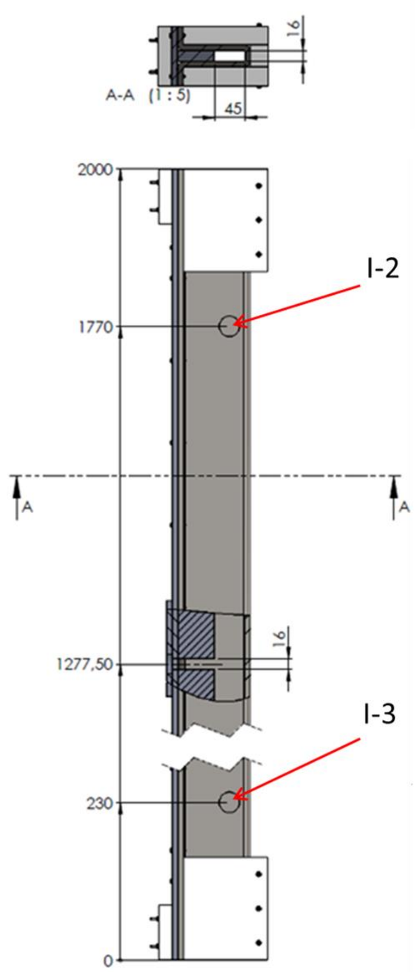

Figure 4: Test section representation: (a) cross section and (b) lateral view
(cut view of the fracture region in detail for e_{FR} = 16 mm)

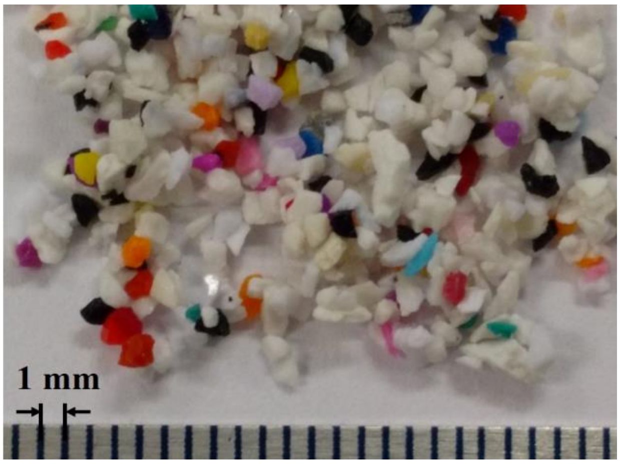

Figure 5: Plastic abrasive (Urea) used as particulate material.

An electronic board connected to the test section performs the signals acquisition from the meters. The system consists of one chassis and three data acquisition modules responsible for acquiring the signal coming from the equipment. The chassis houses the modules and transmits the signals to a computer. Using a programmed virtual interface, the system acquires the equipment current signals and, from calibration static curves obtained through tests, converts them into flow, pressure and temperature values.

(a) (b)

Figure 6: Fracture coupled to test section channel: (a) Tubes representing the fracture (b) fracture overview with fluid flow control valve.

4. RESULTS AND DISCUSSION

The influence of the fracture thickness, the initial flow rate at the fracture outlet and the Reynolds number over the particle bed formation process is investigated. Table 1 shows the parameters for the liquid-solid solution, as well as the tests section geometry in all essays.

Table 1. Parameters used in the experimental tests.

Mass concentration of glycerin in water	C_g	68.90%
Mass concentration of particulate material in the solution	C_p	3%
Particle-fluid density ratio	$\rho_{p/g}$	1.28
Fracture length	h_{FR}	1 m
Channel thickness	h_{CH}	45 mm
Channel depth	Z_{CH}	16 mm
Reynolds number	Re	150 – 300 – 450
Fracture thickness	e_{FR}	16 – 20 – 26 mm
Valve opening of initial flow rate for fracture	Q_V	0.25 – 0.5 – 0.75 – 1.0 – 1.25

The fracture filling process has a deposition rate that decreases in time until a stabilization of the bed is reached. From this moment on particles will no longer enter the fracture and the geometrical parameters, such as the initial position, $h_{p,i}$, extension, h_p , and height, e_p , of the particle bed and also the particles injection time, t_{ip} , as seen in Figure 7, are determined.

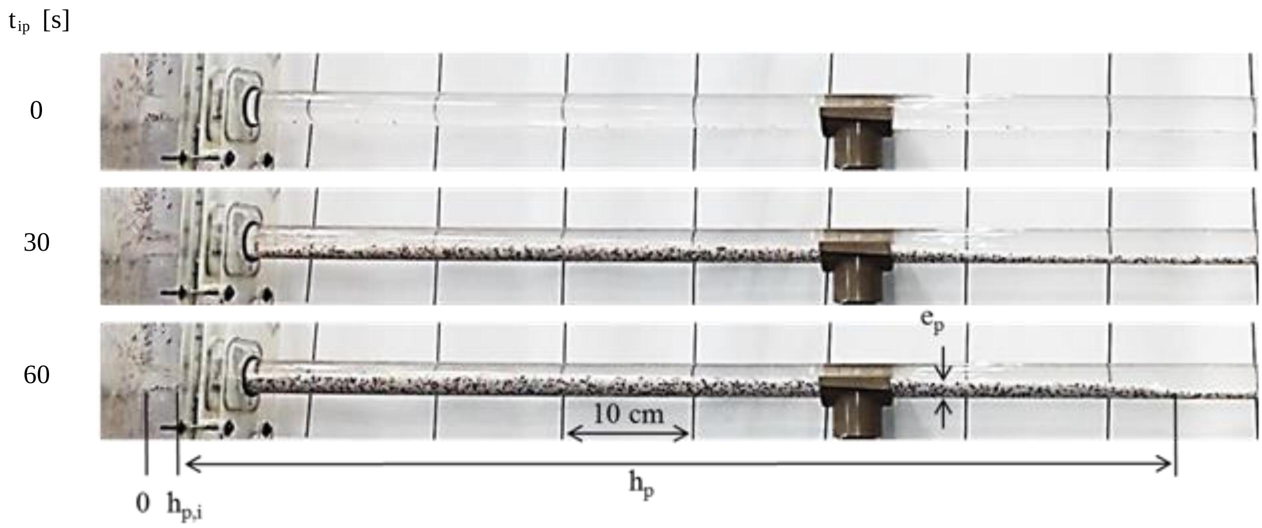

Figure 7: Particle bed geometric parameters over time for e_{FR} = 20 mm, Re = 150 and Q_V = 0.75.

4.1 Fracture thickness effect

Tests to verify the fracture thickness influence were performed for a flow with Re=150 and initial fracture flow rate of ½ valve turn (Q_V = 0.5), using the three fracture thicknesses (e_{FR} = 16, 20 and 26mm). The Figure 8 shows the final particle beds obtained. Particle bed geometric parameters for these tests are shown in Table 2.

In general, the tests performed for the three different fracture thickness, for a certain Reynolds number and constant initial fluid flow rate (opening valve), show that the greater the fracture thickness (e_{FR}) the smallest is the length of the particles bed (h_p), but the higher is the bed height (e_p) and the filling time (t_{ip}). The increase in the fracture flow rate area provides a greater number of particles to enter, which, due to the gravity, tends to be deposited closer to the fracture entrance.

Figure 8. Fracture thickness effect over the filling process for Re = 150 and Q_V = 0.5.

Table 2. Particle bed geometric parameters for each fracture thickness.

e_{FR} [mm]	$h_{p,i}$ [mm]	h_p [mm]	e_p [%]	t_{ip} [s]
16	18	435	50	115
20	22	255	55	120
26	18	176	82	260

Figure 9 shows the pressure gradient during time for the tests with the three fracture thicknesses. The pressure gradient is defined as the ratio of the pressure difference measured between the two transducers ($p_{I,2}$ and $p_{I,3}$) and the distance between the position of the transducers (1.54 m), as presented in Eq.(2).

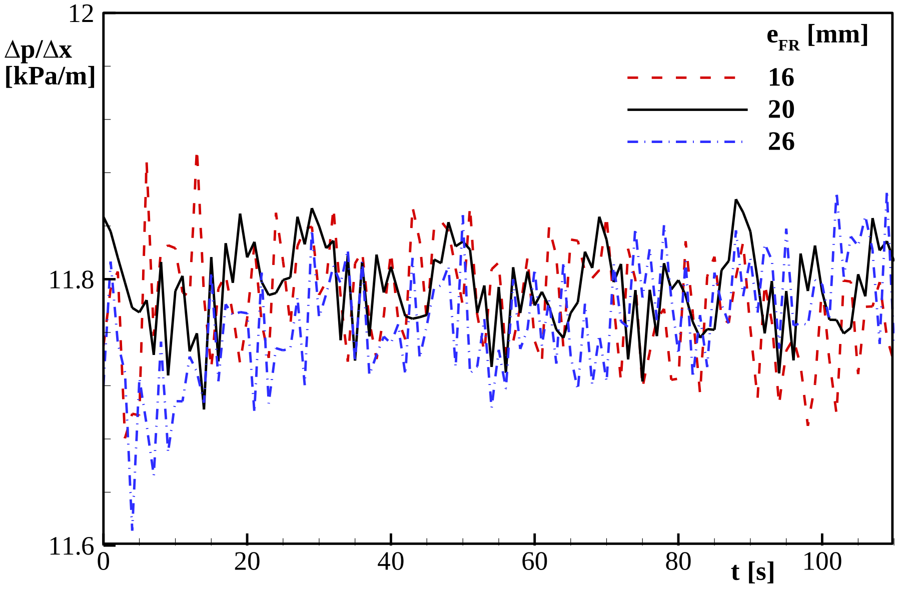

Figure 9: Channel pressure gradient over time for Re = 150 and Q_V = 0.5.

$$\frac{\Delta p}{\Delta x} = \frac{p_{I,3} - p_{I,2}}{1.54} \quad (2)$$

Notice that the fracture thickness variation does not exert a significant influence on the pressure gradient along the channel. Over time, each test also shows no variation in the pressure gradient, but an instantaneous decrease occurring close to 10 seconds, is evident as the fracture end valve is opened. This decrease is more pronounced than the characteristic oscillation of the pressure transmitters, which remains around 0.15 kPa/m.

4.2 Fracture outlet initial flow rate effect

In order to evaluate the fracture initial flow rate influence, the valve positioned at the fracture end was opened in ¼ turns and five different opening levels were compared using the 20 mm fracture thickness (e_{FR}), for Re = 150. Figure 10 shows the final particle bed obtained and its geometric parameters are shown in Table 3.

Q_V

0.25

0.5

0.75

1.0

1.25

Figure 10: Fracture outlet initial flow rate effect over the filling process for e_{FR} = 20 mm and Re = 150.

Table 3. Particles bed geometric parameters for different initial flow rates.

Q_V	$h_{p,i}$ [mm]	h_p [mm]	e_p [%]	t_{ip} [s]
0,25	27	320	65	105
0,5	25	260	58	120
0,75	25	720	60	165
1,0	27	870	64	350
1,25	-	-	-	-

The results obtained by varying the fracture opening valve (or the initial flow rate), for a constant Reynolds number in a fracture with fixed thickness, show that the higher the flow rate (Q_V) the higher is the length of both the formed bed (h_p) and the filling time (t_{ip}). As the fracture admits a higher flow rate, the velocity at the fracture inlet region is increased, allowing a larger amount of particles to enter the fracture. For a determined valve opening (e.g., Q_V = 1.25) no bed formation is verified.

Figure 11 shows the historic pressure gradient for the different fracture outlet initial flow rate. For the case of Q_V = 1.25 a decrease in the pressure value is observed at $t_{ip} \sim 10$ s, since at this instant the channel outlet pressure is not detected, revealing a severe total fluid loss.

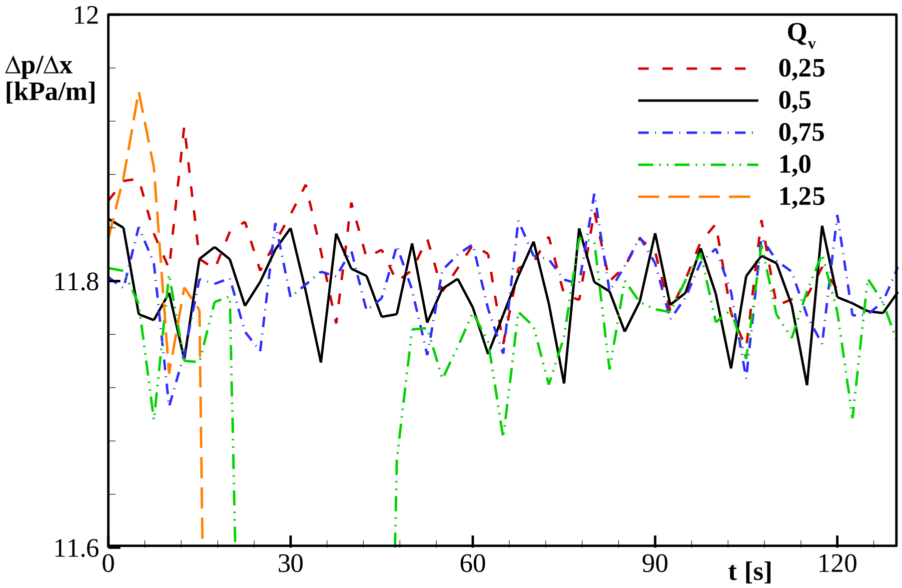

Figure 11: Pressure gradient over time for e_{FR} = 20 mm and Re = 150.

4.3 Reynolds number effect

The particle beds obtained for three different Reynolds numbers for fracture thickness of e_{FR} = 26 mm and initial fracture flow rate Q_V = 0.5 were compared. The Figure 12 shows the stabilized particle beds obtained with Reynolds number of 150, 300 and 450. The particles bed geometric parameters for these tests are shown in Table 4.

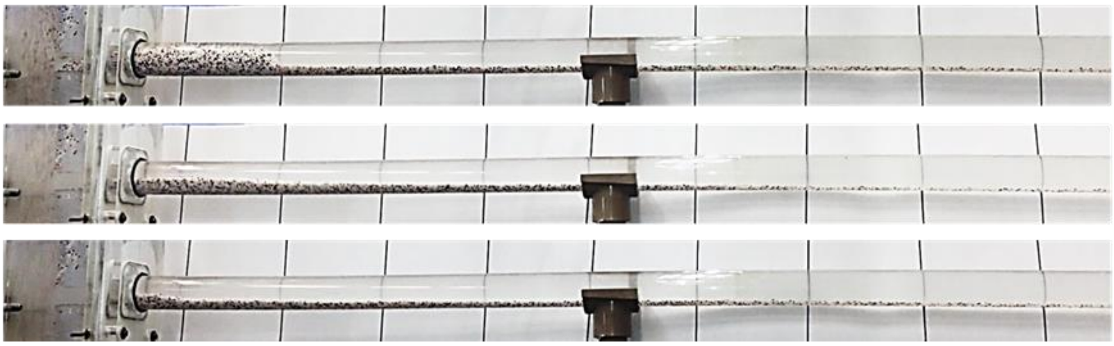

Figure 12: Reynolds number effect over the filling process for e_{FR} = 26 mm and Q_V = 0.5.

Table 4: Particles bed geometric parameters for different Reynolds number.

Re	$h_{p,i}$ [mm]	h_p [mm]	e_p [%]	t_{ip} [s]
150	18	176	82	260
300	45	125	40	50
450	60	36	35	40

Tests for different values of Reynolds number in the channel show that as the flow inertia increases with the Re, fewer particles will enter the fracture. Another aspect related to the bed initial position, which significantly increases with increasing Re, is observed due to the high inertia that the particles present within the fracture. In such configurations no particle bed is formed, which represents a total fluid loss through the fracture.

The Figure 13 shows the pressure gradient in the test section over time for the different Reynolds number. The pressure gradient presents a slight increase as the Reynolds number also increases.

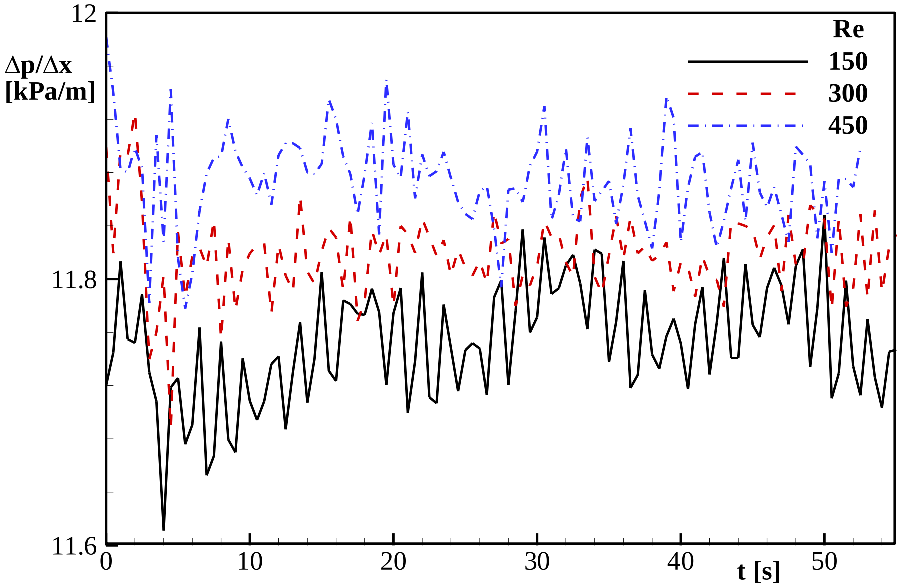

Figure 13: Pressure gradient over time for e_{FR} = 26 mm and Q_V = 0.5.

5. CONCLUSION

In this work, the loss of fluid circulation in a vertical channel due to a transversal fracture is investigated experimentally. The fluid loss is reduced by releasing particulate material in the flow to promote the fracture filling. In general, the results show that the fracture thickness, the initial fracture flow rate and the channel Reynolds number are able to modify the geometric characteristics of the bed, having a direct influence on the flow rate, on the amount of particulate material and on the time required to obtain the final bed. In the fracture thickness variation tests, the increase of the flow area by the fracture elevates the number of particles to enter. This happens due to gravity and the particles tend to settle closer to the channel inlet, resulting in higher and less extended beds. It has been observed that the higher the initial fracture flow rate, the longer the formed bed and the filling time. The increase in the initial fracture flow rate results in a higher velocity in the fracture inlet region, allowing a larger amount of particles to enter the fracture and a larger particle bed. For a given valve opening a total fluid loss by the fracture occurs, impeding the flow circulation through the channel outlet. Such severe losses, related to the high velocities in the fracture, increase the flow inertia, being able to carry the particles, avoiding the bed formation. For the Reynolds number variation, it was verified that smaller values provides a larger amount of particles to enter the fracture, resulting in better filling formats. As the Reynolds number increases the flow inertia on the fracture region entrance becomes higher, hindering the entry of the particulate material on the fracture.

6. ACKNOWLEDGEMENTS

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