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A real-time flow-measuring algorithm for open Venturi channel non-Newtonian flow

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Abstract

A real-time flow measuring algorithm is developed for the open Venturi channel non-Newtonian flow measurement. Using a single level sensor reading at downstream of the open Venturi channel, a drilling-well return flow rate can be calculated in real time. The experiments are conducted with different flow rates with step changes in pump outlet flow rate. The Coriolis flowmeter readings used to validate the calculated flow rates based on the level sensors. Three levels sensors record the reading when channel at a horizontal inclination. The level sensors are located at upstream of the Venturi contraction, near to the Venturi contraction and after the Venturi contraction. The minimum error occurs from the level sensor located near to the Venturi contraction. The strong subcritical flow regimes give a less disturbance for real-time flow measurements. The 1-dimensional flow model well employed subcritical flow than the supercritical flow. We recommend locating the level sensor near to the Venturi contraction, where the maximum subcritical flow occurs.

1 Introduction

Open Venturi channel Newtonian and Non-Newtonian flow models were developed in our previous studies (Welahettige et al., 2018, 2019). In this study, we develop a real-time flow-measuring algorithm to measure the mud return in well drilling in open Venturi channels. The motivation behind the study is to develop a new flow sensor technology for the kick and loss detection in well drilling. Agu et al. (2017) introduced a flow measuring algorithm for open channels, using two sensor readings. Jinasena et al. (2018) proposed a model based real-time flow rate estimation method for open channel.

2 Experimental setup

The objective of the flow measurement is to find the channel inlet flow rate, which is equal to the pump outlet flow rate. In the real field, the wellbore outlet flow rate is equal to the channel inlet flow rate. Figure 1 shows the flow loop of the experimental setup. Three level sensors are used to measure the flow depth of the open Venturi channel, and a Coriolis flowmeter is located between the buffer tank and the mud pump. The Coriolis flow meter readings are used to validate the numerical result. The ultrasonic level sensors accuracy is ±0.25 %, and the Coriolis mass flow meter accuracy is ±0.1 %.

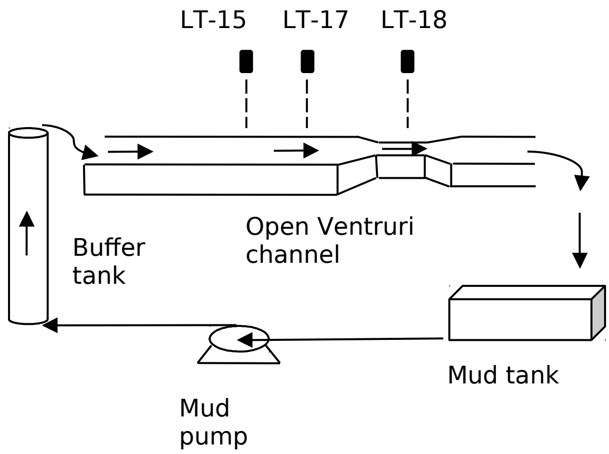


Figure 1. Flow loop of the experimental setup: The Coriolis flow meter is located between pump outlet and buffer tank. Three level sensors LT-15, LT-17 and LT-18 are located along the channel central axis.

3 Algorithm for flow rate calculation

The Saint-Venant equations for the non-Newtonian turbulent flow can be present as follow (Welahettige et al., 2019),

$$\frac{\partial A}{\partial t} = \frac{-\partial (Au)}{\partial x},$$

$$\frac{\partial(AV)}{\partial t} = \frac{-\partial(AV^2)}{\partial x} - \frac{\partial(k_{g_1} Ah)}{\partial x} g + k_{g_2} h^2 g \frac{\partial b}{\partial x} + Ag\sin \qquad (2)$$

.

Here, A is the cross-sectional area of the channel, which is a function of flow depth h. V is the average velocity, k_{g_1} and k_{g_1} are model parameters, α is the channel inclination angle, S_e is the external friction slope, S_i is the internal friction slope, b is the bottom width. The internal friction slope is calculated from based on the Herschell-Bulkley model, and the external friction is calculated from the Manning's friction model (Welahettige et al., 2019). The FLIC scheme and Runge-Kutta 4th order explicit scheme are used to solve the Equation-1 and 2. The finite volume method is used to discretize the fluid domain.

The algorithm is developed to calculate the inlet flow rate of the channel by using the level sensor readings at downstream, see Figure 2. Here, we used only one level sensor reading to measure the flow rate in the open Venturi channel. The buffer tank outlet flow enters to the channel in gravity. The buffer tank inlet is elevated from the channel bottom level, which can be elevated up to 2-3 times of flow depth. Therefore, the flow regimes are always supercritical at the inlet. The inlet flow depth can keep as a constant by varying the inlet velocity to calculate the flow rate. We have noticed that same flow depth can achieve in the downstream for different inlet flow depth but same flow rate. The contraction section of the open channel makes a significant variation of the flow regimes. The upstream hydraulic jump neutral the inlet variation between the A and V for the same flow rate.

Previous time step conserved variables are used as the initial condition for the spatial domain. When the iteration starts the first time, the initial conditions are fixed to low flow depth and low velocities. This method might help to avoid unnecessary large the overshoot and undershoot in the numerical result.

Step-1: Calculate the h and V for the whole fluid domain from the interface fluxes. The FLIC scheme and the source term splitting method can be used (Toro, 2009; Welahettige et al., 2018). Here, $i = 1, 2, \ldots L$. L is the last control volume of the 1-D fluid domain.

Step-2 and Step-3: Calculate for the time iteration for the all the control volume. Calculate until $t = T$, where T is the step length of the level sensor reading.

Step-4: Check the difference between calculated flow depth (h_c) and the measured flow depth (h_m) at the same location of the channel. If the difference is an acceptable level, the flow rate is $Q = A_0 V_0$. If not, set the inlet condition into new values. Here h_c is the calculated flow depth of a control volume where it is the same location of the level sensor.

Set: $h_m > h_c$ means, the guessed inlet flow rate is lower than the actual flow rate. Therefore increase the inlet flow velocity by $V_0 = V_0 + \Delta V$. $h_m < h_c$ means, the guessed flow rate higher than the actual flow rate. Therefore reduce the inlet flow velocity by $V_0 = V_0 - \Delta V$. Then return to the step-1.

4 Results

The real-time experiment results used to validate the numerical model result. The open Venturi channel is at the horizontal inclination. The level sensors LT-15, LT-17 and LT-18 are located at the centerline of the channel, and the distances from the inlet of the channel are 2.12 m, 2.42 m and 3.2 m respectively. The level sensors readings (experimental results) are shown in Figure 3. The step changes occur at $t = 35$ s and $t = 158$ s. Due to the turbulent wave motion, a noisy result came out from the level sensors. LT-15 level height is comparatively small all the time, which is due to the level sensor located at transitional region of supercritical to subcritical flow. Generally, the supercritical flow has a lower flow depth than the subcritical flow. The level sensors LT-17 and LT-18 show similar flow height even though they are placed before and after the Venturi contraction.

Based on the level sensor online measurements, the flow rates are calculated using the developed algorithm. Figure 4 shows a comparison of the calculated flow depth and the Coriolis flowmeter reading in the real time. We want to emphasize the flow measuring ability, at the real-time in this study. Therefore, the experimental results are raw data, without smooth by the filtering. Figure 4 shows the calculated flow rate and the Coriolis flowmeter reading in real time based on the level sensor readings. Compared to the LT-18, the LT-15 and LT-17 readings give a good match with the pump outlet flow rates.

5 Discussion

The calculation speed can improve by increasing the Δh and ΔV values. However, the values affect the accuracy of the results. Here we selected 0.0001 for both Δh and ΔV. The level sensors recorde on every second. The number of iteration required to achieve 1 s of flow time is $N \approx 350$ in this study. However, we recommend achieving a steady state numerical result before starting the on-line measurement. A steady-state result can achieve by setting $N \approx 30000$ for first level sensor reading. After that, it can set to $N \approx 350$. This method increases the accuracy and reduces numerical viscosity. Depending on the channel geometry, fluid properties, and flow rate, those N values can vary.

The flow rate calculates $Q = AV$, and here have two unknown parameters A and V. To solve the Saint-Venant equations, the inlet boundary condition needs to know. In this study, we noticed that by keeping constant the Inlet A, and allowing for varying the parameter V for the same flow rate freely, can achieve the same condition downstream of the channel. Figure 5 shows a steady state flow depth variation along the channel central axis for different inlet conditions by maintaining the same inlet flow rate of 400 kg/min. The inlet flow depth varies 0.01 m to 0.025 m. However, all the cases give same flow depth near to the Venturi region and after the Venturi region. Varying only the velocity at the inlet of the open Venturi channel, same flow condition can achieve near to the Venturi contraction region. This method is quite essential for easy numerical calculations. We selected channel inlet flow depth as 0.02 m for the all the simulations flow rate 100 kg/min to 700 kg/min. The maximum flow depth achieves in all the simulations less than 0.1 m. We recommend selecting inlet flow depth minimum five times lower than maximum flow depth. Otherwise very high inlet flow velocities increase the numerical viscosities.

The average error between the numerical and experimental results are calculated from, $\frac{1}{N_{total}} \sum_{j=1}^{T_{end}} \left| \dot{m}_{m,j} - \dot{m}_{c,j} \right| / \dot{m}_{m,j}$. Here, $\dot{m}$ is the mass flow rate, T_{end} is the end time, N_{total} is the total number of level sensor readings. The average errors are 6.3 %, 4.1 % and 13.8 % respectively from LT-15, LT-17 and LT-18 level sensors based flow rate calculations. Based on this result, we can conclude that the best location to place the level sensor is near to the Venturi contraction (just before the Venturi contraction begins). Near to the Venturi contraction, flow regimes are stable compared to the other region of the channel. Minimum disturbances occur near to the Venturi contraction due to strong subcritical flow.

Even though the sudden step changes occur in the pump outlet flow rate, the simulated results gradually vary the flow rate. The time required to reach the level sensors location of the fluid flow might be the reason to make a difference between the experiment and the simulation at the step changes. The algorithm is suitable for online flow rate measurement in given viscosities and densities. Further, it needs to develop for online varying viscosity and density parameters of the return fluid.

6 Recommendations

- Place the level sensor near to the Venturi contraction (just before the Venturi contraction begins) for accurate flow measurement, when channel inclination at horizontal.

- After reach to the steady-state numerical condition, start the online measurement: This increases the stability of the algorithm.
- If the channel length very long after the Venturi region; the fluid domain after the Venturi region might be insignificant.

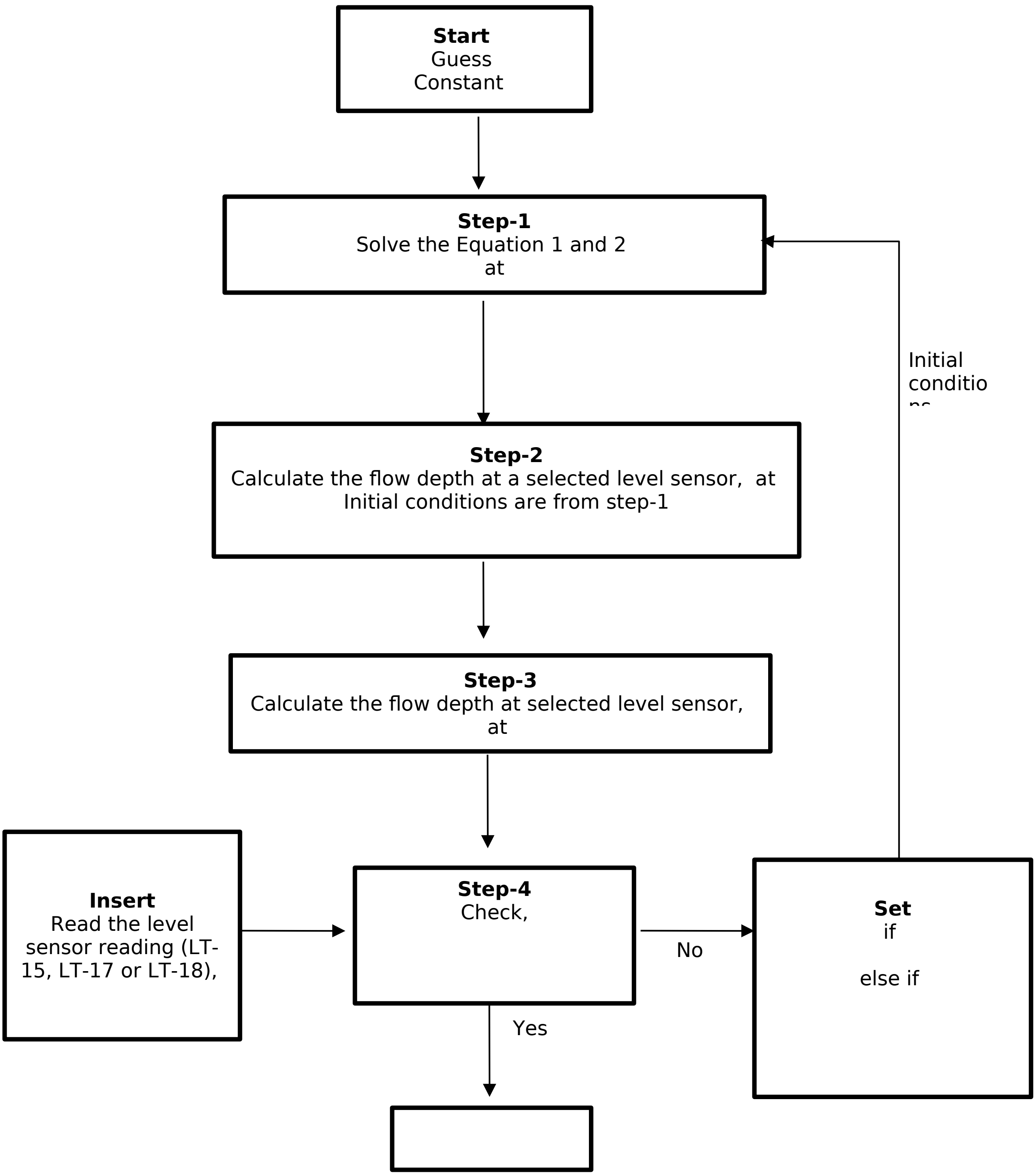


Figure 2. Algorithm for calculating the open Venturi channel flow rate in real time.

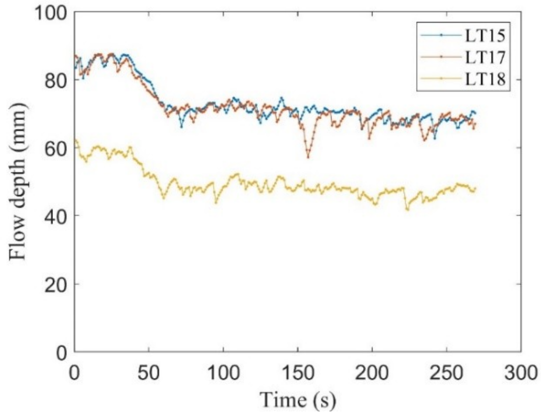
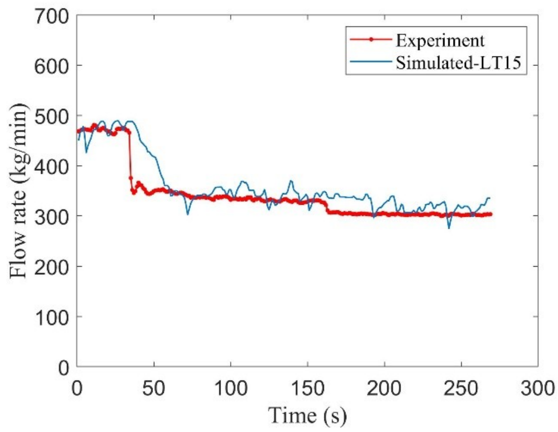
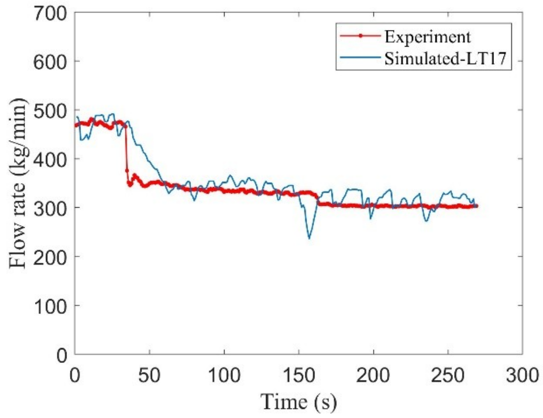


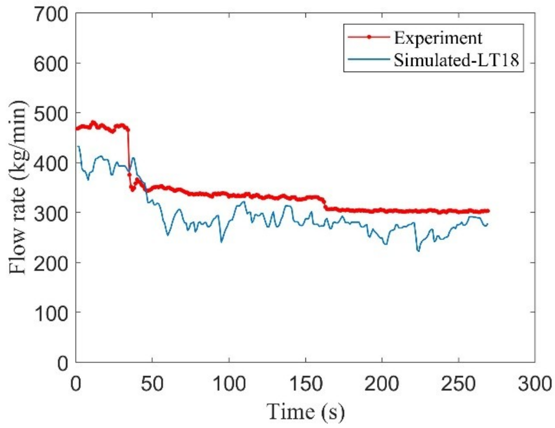
Figure 3. The real-time experimental results of level sensors readings. The channel angle is at horizontal.



(a)



(b)



(c)

Figure 4. Mass flow rate experimental and simulated when the channel inclination at horizontal: (a) Flow rate calculation based on LT-15 level sensor reading

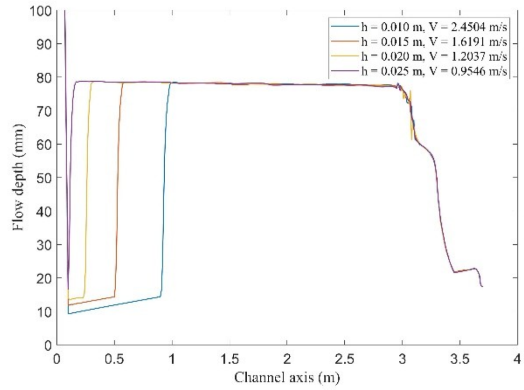


Figure 5. At steady state flow depth variation along the channel axis for different inlet condition for the same flow rate of 400 kg/min.

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