DIGITAL FLOW CONTROL UNIT FOR CONTROLLING AMOUNT OF WATER USED FOR BINDING DUST

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ABSTRACT

Rock drilling requires that the rock dust formed during drilling is removed with flushing. Nowadays, liquid mist is often employed to bind dust from the flushing air in overground drilling. The amount of the liquid, for example water, is precise, because too small or too large amount of liquid leads to unwanted result. Traditionally, the liquid amount is controlled by a manual valve in the control cabin of the drilling machine. This method has disadvantages and therefore, some alternative control systems have been considered. This paper presents a 7-bit Digital Flow Control Unit (DFCU) which was designed for controlling the amount of water in the dust binding system.

KEYWORDS: Digital Flow Control Unit, On/Off valve, Rock drilling, Dust binding

1. INTRODUCTION

There are some means to remove the rock dust formed during drilling, for example air flushing. Nowadays it is common to employ liquid mist to bind dust from the flushing air. Dust binding is important because dust may cause health hazard. For example, silicosis is one potential occupational disease after long exposure [1]. Dust can also increase accident risk in the working area and drilling rig (Figure 1) may require more maintenance because of getting dusty.

Figure 1. Surface top hammer drilling rig.[2]

The main components for separating rock dust from the flushing air are introduced in Figure 2. They are suction nozzle (4), suction hoses (5&7), pre-separator (6) and dust separator (8). The basic idea of binding dust with water mist is simple, but reasonable result requires rather good controllability. The amount of the liquid, for example water, is precise, because too small amount of liquid does not bind rock dust and too large amount of liquid may block up the dust removal equipment. At present, the liquid amount is controlled manually by a valve in the control cabin. This means that the hose must be circulated via cabin which a disadvantage of this method.

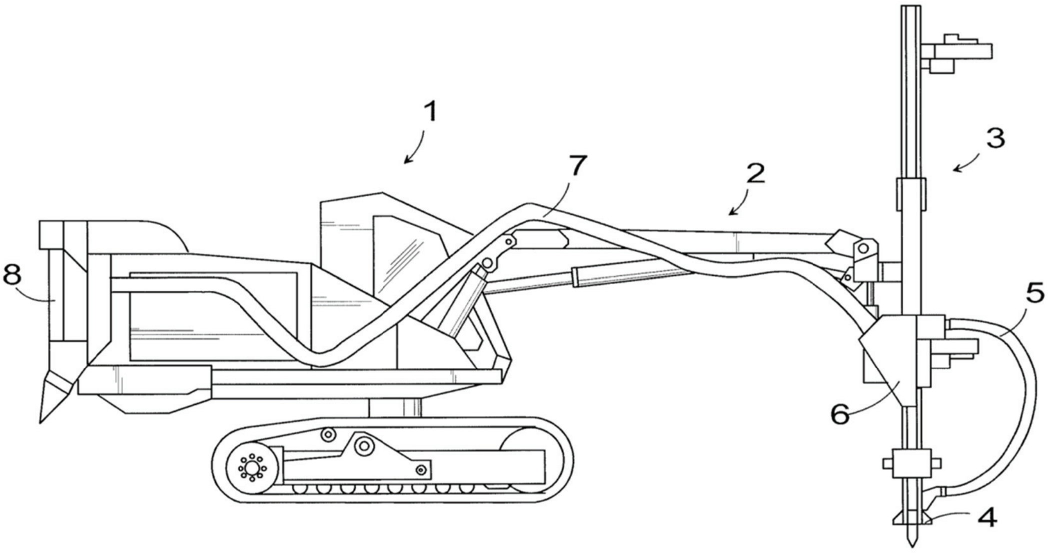

Figure 2. Rock drilling rig with a dust binding system. [3]

The dust binding system utilizing water mist can be improved by using electrically controlled valve. However, there is lack of suitable valves because the properties of water place some special requirements (corrosion resistance, tight tolerances etc.) for the valves. In addition, high-quality water hydraulic valves are produced only in limited quantities which increase their price significantly. One way to tackle these problems is using simple and low-cost on/off solenoid valves with a suitable control method.

This paper presents a 7-bit Digital Flow Control Unit (DFCU) which was designed for controlling the amount of water in dust binding system. First measurements and calibration were made in the laboratory circumstances and later, the system was tested also in a rock drilling rig.

2. DFCU FOR DUST BINDING SYSTEM

Lack of suitable water hydraulic valves with reasonable price forces to seek alternative solutions for controlling amount of water in dust binding system. On/off valve with simple and robust design has typically low price, but there are only a few possible ways to implement flow control system with on/off valve.

2.1. Flow Control with On/off Valves

Over the last few decades, Pulse Width Modulation (PWM) has been the most widely applied on/off control method in fluid power systems with several commercial applications, e.g., the anti-lock braking system. The mean flow of a PWM-controlled valve is determined by its ratio of open to close periods. Therefore, PWM control requires high frequency and continuous switching of the valve between open and closed positions. The main challenge of PWM control in dust binding system is that its high frequency switching sets requirements for the valve's durability. In addition, flow ripple can be intolerable without any compensator at low flow rates. [4]

The other possible control approach is based on a number of parallel connected on/off valves. System of this type is known as Digital Flow Control Unit, DFCU (Figure 3). Flow paths of the DFCU can have identical flow rates (Pulse Number Modulation, PNM) or they can be set according to some coding scheme, e.g., binary coding [5]. DFCU provides fast and accurate control together with good fault-tolerance. Especially the latter one is important in rock drilling circumstances. Available water can be dirty which may easily cause malfunction of the valves. Service life of the valves in the DFCU is also expected to be longer than in PWM controlled system because when the circumstances and flow reference are constant, valves of the DFCU do not need to change their state.

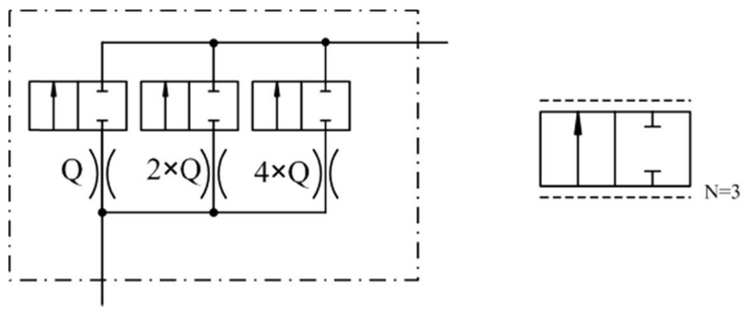

Figure 3. Binary coded DFCU and its simplified drawing symbol. *N* defines the number of parallel connected valves [4].

2.2. Requirements and Specification of the DFCU

Dust binding system does not have own water pump but water is pressurized with an air compressor (Figure 3, 11) which is used also for air flushing. General schema of the flushing system is shown in Figure 4.

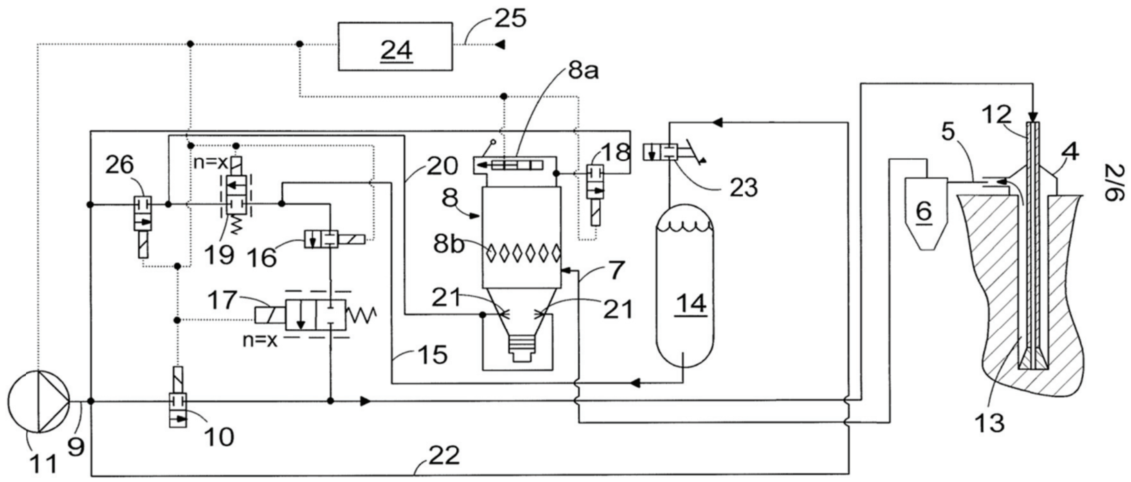

Figure 4. Dust binding system with a Digital Flow Control Unit (17). [3]

The pressure difference between the input and output side of the DFCU is measured and valves are controlled according to the pressure differential so that the flow rate remains substantially constant. Pressure differential variation must be considered in the system design because required maximum flow rate must be fulfilled at minimum pressure differential whereas step size H should not be exceeded at maximum pressure difference. To get suggestive number of flow steps (N_{steps}) and valves (N), the following equation can be used:

$$N_{steps} = \frac{Q_{max}}{H}\sqrt{\frac{\Delta p_{max}}{\Delta p_{min}}} \qquad \text{(Eq. 1)}$$

where N_{steps} is the needed number of flow steps [l/min]
Δp_{max} is maximum pressure difference [MPa]
Δp_{min} is minimum pressure difference [MPa]
Q_{max} is required maximum flow capacity [MPa]
H is step size [l/min]

The number of flow steps depends on how many valves are used but even more significant is the coding scheme. The Pulse Number Modulated (PNM) DFCU offers as many flow steps as there are valves connected in parallel whereas in the binary coded DFCU the maximum number of flow steps is 2^N-1. This means that binary coded DFCU has clearly smaller physical size than PNM coded DFCU when the same valve model is utilized.

Minimum pressure differential of the system is about 0.2 MPa and maximum pressure differential about 0.4 MPa. Required maximum flow rate is 5 liter/min and step size should be 0.1 liter/min. Based on the Equation 1, adequate number of flow steps is 71 with the above values. However, this result is only suggestive because of the practical issues. Steps sizes are not identical and coding scheme affects also on the

characteristics. PNM coding requires that 71 valves must be connected in parallel but with the available valve models this is not yet possible to complete in practice. Instead, binary coding was chosen for this application because it does not require as much valves as the other coding schemes. Binary coded DFCU with six valves provide 63 flow steps but it is not fairly enough and accordingly, seven valves are needed.
Valve does not need to be extremely fast acting in the dust binding system but switching time can be 0.01-0.05 s, or even slower. Certainly, faster valves provide better controllability, but the above switching times are acceptable.

IHA has long experience in low pressure (<5 MPa) water hydraulics and based on the earlier projects, Flo Control Q2R-B valve model was chosen for this dust binding system. It is not the only option but similar valves can be found on the market. Flo Control has two possible options for this application, Q2R116 and Q2R124 valves. They both are unidirectional and normally closed on/off valves. Their flow capacities are 1.7 liter/min and 3.5 liter/min at 0.1 MPa pressure differential and maximum operating pressures of the valves are 3.5 MPa and 1.5 MPa. According to manufacturer, response time of the valves is 0.006-0.018 s. [6]

Total flow capacity of the binary coded DFCU is approximately $2 \times Q_N$, where Q_N is the flow capacity of the biggest valve. This means that the estimated flow capacity of the DFCU at 0.2 MPa pressure differential is 4.8 liter/min (Q2R116) or 9.9 liter/min (Q2R124). Q2R116 seems to be slightly undersized and therefore, Q2R124 model was chosen. Figure 5 shows the first prototype of the DFCU with seven Flo Control valves.

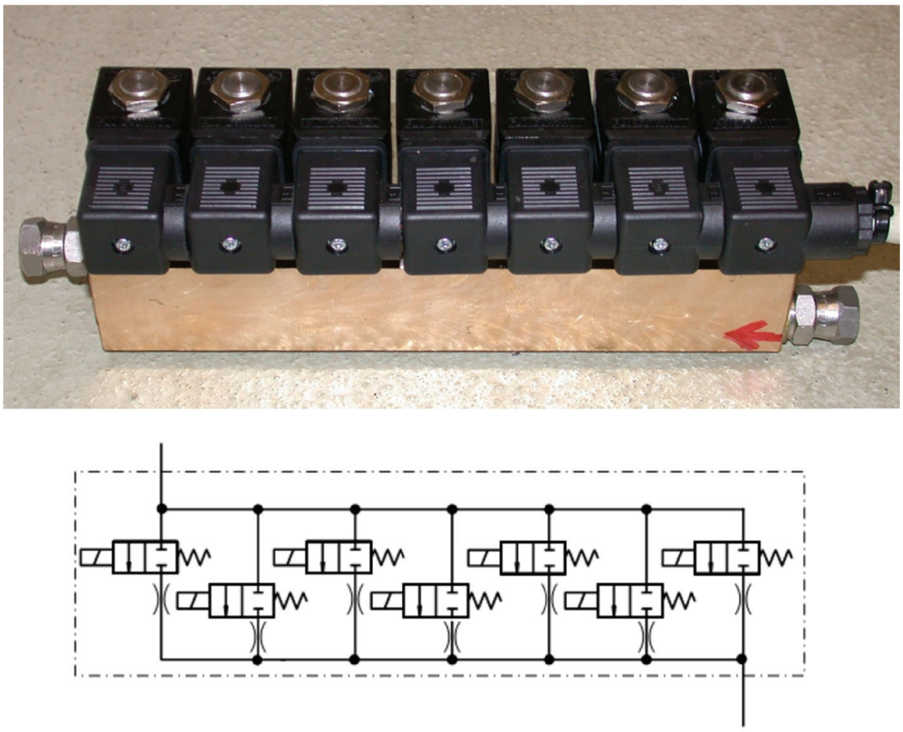

Figure 5. The first prototype of the DFCU.

2.3. DFCU Calibration

The first experimental measurements and calibration of the DFCU were made in the laboratory where all necessary measuring instruments were available. Table 1 introduces measured flow capacities of the different-size orifices. Orifices were available at 0.1 mm intervals, and accordingly, flow capacities are hard to set into ideal ratios. The orifice sizes of the DFCU are 0.3, 0.4, 0.6, 0.8, 1.1, 1.4 mm and the last valve is without orifice. Target pressure differential in the measurements was 0.3 MPa and based on these measurements, flow capacities are estimated at different pressure differentials (see Table 1.)

Table 1. Measured and calculated flow rates with different-size orifices.

	Measured values		Calculated flow capacities		
Orifice	Q [l/min]	Δp [bar]	Q [l/min] at Δp=2 bar	Q [l/min] at Δp=3 bar	Q [l/min] at Δp=4 bar
0.3	0,09	3,16	0,07	0,09	0,10
0.4	0,19	2,91	0,16	0,19	0,22
0.6	0,39	2,92	0,32	0,39	0,45
0.8	0,64	3,03	0,52	0,64	0,73
1.1	1,24	3,02	1,01	1,24	1,43
1.4	2,07	2,95	1,71	2,09	2,42
--	4,00	2,88	3,33	4,08	4,72
		Q_{total} =	**7,12**	**8,72**	**10,07**

In binary coded DFCU, flow capacity of the N^{th} valve should be two times bigger than in $(N\text{-}1)^{th}$ valve. Table 1 shows that the valve 3 with 0.6 mm orifice has slightly too high flow capacity. At first, 0.5 mm orifice was tested but it had clearly too small flow capacity and hence, the sizing error caused by the 0.6 mm orifice was accepted.

Figure 6 introduces all flow rates of the DFCU. There are some discontinuations because orifices were available only at 0.1 mm intervals. This is not a problem but the unnecessary states can be ignored. After this process, characteristics curve looks like in figure 7.

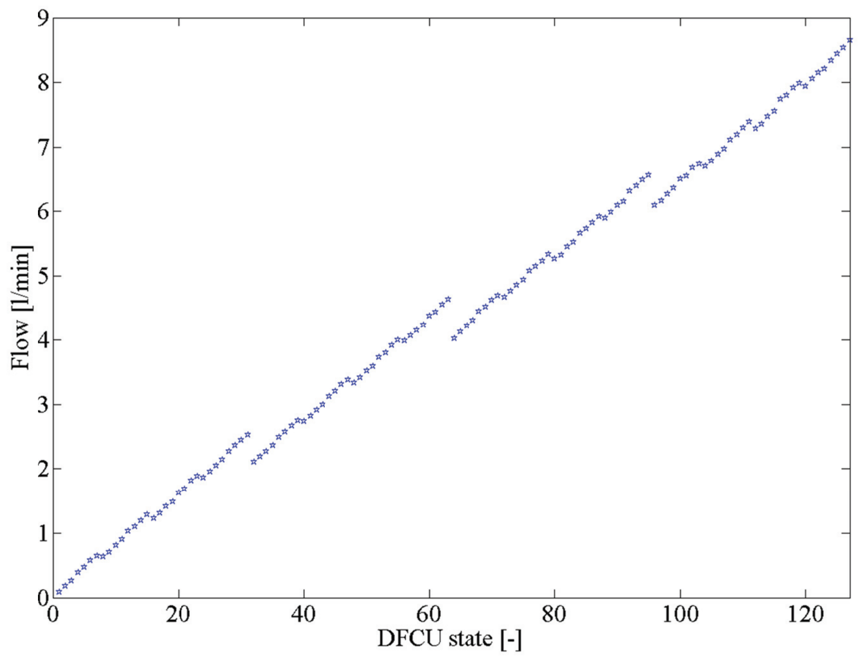

Figure 6. Flow rates of the DFCU

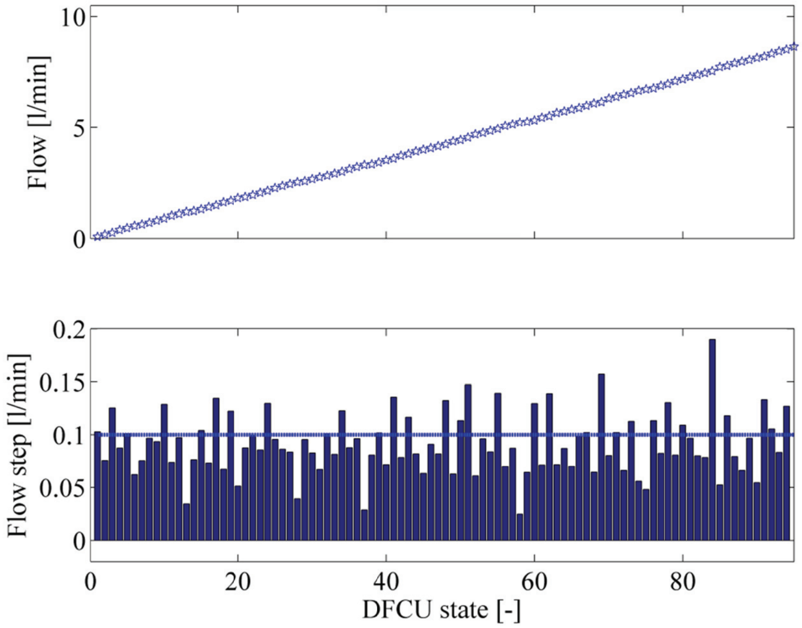

Figure 7. Final flow rates and steps of the DFCU.

Figure 7 illustrates also the flow step sizes. They are not always less than 0.1 liter/min which was the target value. These inaccuracies are caused by slightly too high flow capacity in some valves. However, the fine tuning with the optimal orifices makes it possible to achieve the required accuracy.

Required control accuracy was tight in the first prototype, but in practise it can be lower. Reducing the number of valves is a clear goal because extra valves increases purchase costs and physical size of DFCU. In this study, the number of valves was not optimized but the measurements were made with seven valves.

3. DUST BINDING SYSTEM IN PRACTICE - EXPERIMENTAL MEASUREMENTS IN THE ROCK DRILLING RIG

Dust binding system with the prototype DFCU was tested also in authentic circumstances in Sandvik Pantera 1500, which is a hydraulic, crawler-based surface top hammer drilling rig. Manually controlled flow control valve of the dust binding system was replaced with the DFCU and pressure transmitters for input and output pressures were added to the system. Kobold DPM-1150 flow measuring instrument was used in these experimental tests in the drilling rig. Sampling time of the measurements was 0.01 s.

Flow rate is measured in these experimental tests, but it is not used in the DFCU controller. This decreases purchase cost of the dust binding system in the end product and in addition, there is one component less to failure. Certainly, absolute accuracy of the open-loop system is not necessarily good, but it is not even required in the dust binding system.

Flow reference determined by the drilling rig operator is one input of the controller and based on the tabulated flow rates of the different valves, DFCU's controller chooses the best valve combination. The prevailing pressure difference over the DFCU is taken into account to achieve required flow rate.

Pressure signals have often disturbances which may cause unnecessary valve switching. This can be tackled by using suitable filter. In this study, it was based on the discrete 2nd order transfer function which had break frequency of 15 rad/s and damping ratio of 0.8. Unnecessary valve switching was limited also by using sample time of 0.3 s in the controller. Due to nature of the dust binding system, slow sample time does not dilute quality of the control system too much, but it limits unnecessary valve switching effectively.

Figures 8-11 introduce experimental measurements from the drilling rig. In the Figure 8, drilling has no yet started and pressures are undisturbed. In Figures 9 and 10, drilling has started and it causes oscillations into the outlet pressure. However, valves are not operating hyperactively, because sample time is slow and pressure differential signal is filtered. Certainly, slow sample causes short-term flow rate errors, but they are insignificant in this system. In figure 11, outlet pressure is altered in order to define that how big flow error this can cause.

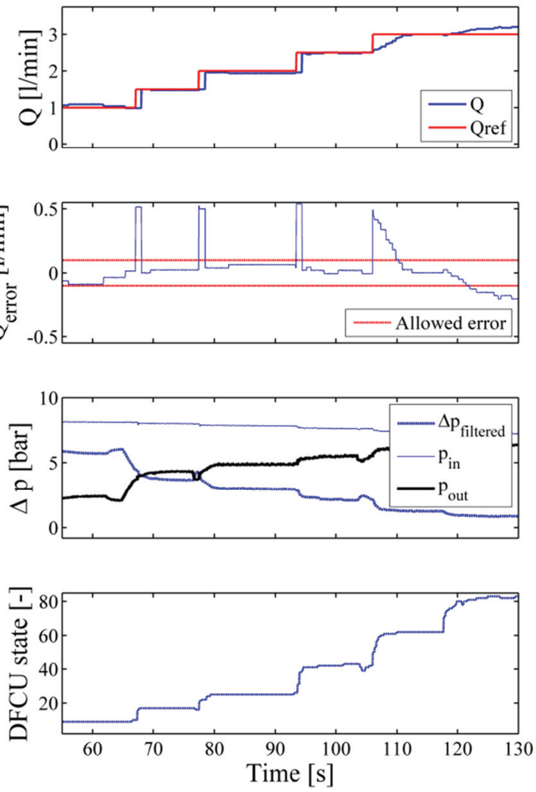

Figure 8. Q_{ref} is increased stepwise

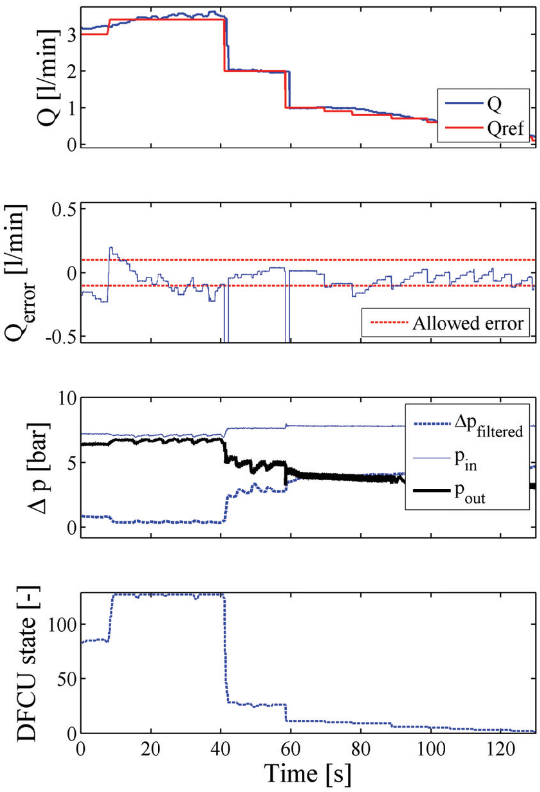

Figure 9. Q_{ref} is decreased stepwise

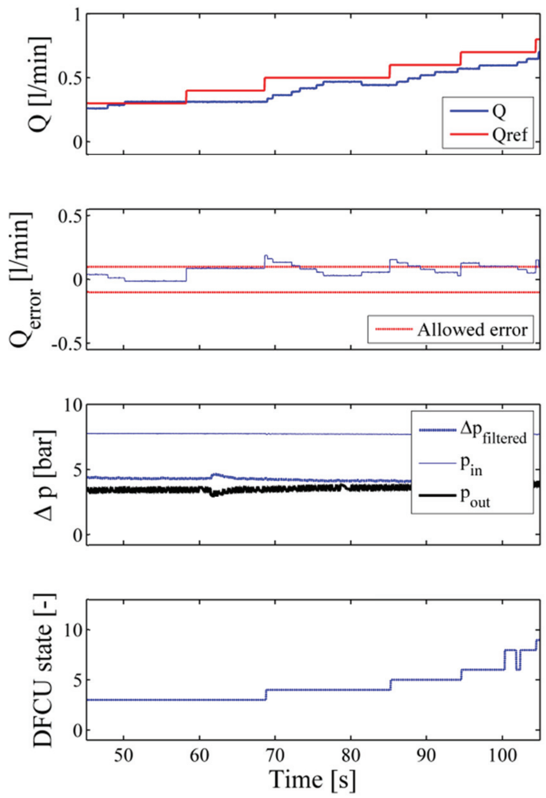

Figure 10. Controllability at low flow rates (<0.8 l/min).

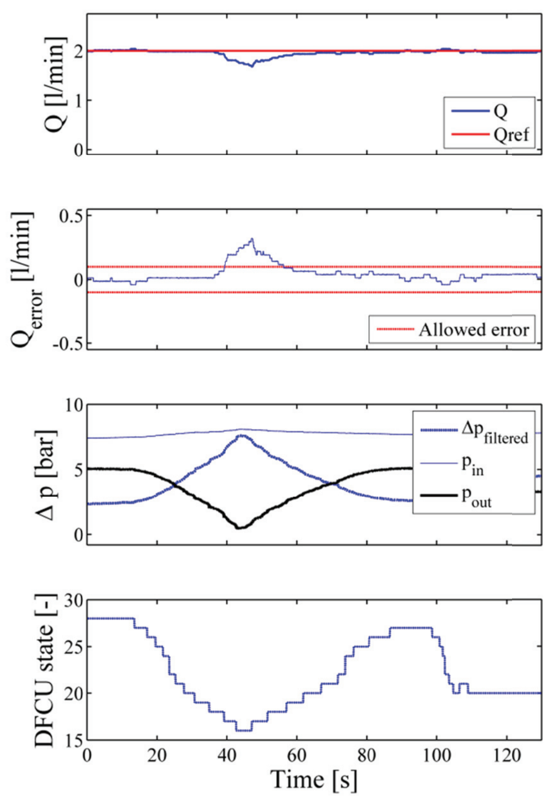

Figure 11. Q_{ref} is constant (2 l/min), but p_{out} is altered.

4. CONCLUSIONS

Liquid mist is used commonly to bind dust from the flushing air. System requires rather good accuracy and the operational environment is demanding for the valves. Water hydraulic proportional valves are expensive and they can be unreliable in rock drilling circumstances where pure water is not always available. Instead, digital hydraulic approach provides an interesting and low-cost alternative. This research shows that flow control system is possible to implement with simple parallel connected on/off valves and without closed-loop control. Certainly, absolute accuracy of the open-loop system is not excellent, but in the dust binding system it does not matter because the human operator in the drilling rig cabin is making the final decisions of the reasonable flow rate.

Although the system is not fully automatic, DFCU eases operator's job, because pressure fluctuations do not change flow rate significantly. In addition, fault-tolerance of the DFCU is better than in proportional valves because malfunction of some on/off valve(s) does not paralyze the whole flow control system. Certainly, water impurities may have an effect also on the DFCU and this must be taken into account in the DFCU design. For example, the minimum orifice diameter should be 0.3 mm or more if proper water filtration system is not used in the dust binding system.

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