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Development of speed controlled pigging for low pressure pipelines

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ABSTRACT

In this study we investigate the development of a speed controlled pig in a low pressure pipeline. This is known to be a challenge due to the compressibility of the gas which can induce velocity surges of the pig. In order to reduce these velocity surges, a speed controlled pig with active by-pass control has been designed, fabricated and subsequently tested on a laboratory scale. The experimental setup consists of a 52 mm diameter pipe with a length of 62 meter. The working fluid is air. The speed controlled pig has an adjustable by-pass valve which can provide the right amount of by-pass to regulate the by-passing fluid force. First test runs show that the velocity surges can indeed be reduced, which demonstrate the feasibility of realizing fully autonomous control for by-pass pigs in low pressure pipelines.

1 INTRODUCTION

Pipeline maintenance in the oil and gas industry is usually done with a so-called ‘pig’, which is a cylindrical or sometimes spherical device travelling through the pipeline while being propelled by the production fluids [8, 10]. Such pipelines can transport oil/water, dry gas, or multiphase flow such as gas/condensate/water.

When operating under low pressure conditions, while the flow is gas-dominated, the compressibility of the gas may lead to an unsteady, oscillatory motion of the pig through the pipeline. This is because compressed gas pockets may build up behind the pig when it is moving slower due to for example irregularities in the pipe diameter. When the pressure build-up in such a pocket is sufficiently high, it is able to catapult the pig, resulting in high pig velocity excursions. This can lead to an unsafe and inefficient pigging operation. It can even result in a so-called ‘stick-slip motion’, where the pig slows down completely after a period of high velocity. Apart from possible damage that can occur to the pipe or the pig, velocity excursions may have an adverse effect to the quality of the inspection data that are collected during an intelligent pigging run [9, 11]. It is therefore desired that the velocity of the pig is controlled in low pressure gas-dominated pipelines.

A way to control the pig velocity is through the use of an adjustable by-pass area, which allows a certain part of the production flow to by-pass the pig. As the size of the by-pass determines the pressure drop over the pig [1,3] it is possible to adjust the by-pass in such a way that the friction force of the pig with the pipe wall is exactly balanced at a certain target pig velocity. A few studies discuss how speed control can be obtained by actively adjusting the by-pass area [4, 7, 11, 12, 13].

In the present work we describe the design of a speed controlled by-pass pig and subsequent lab experiments in a 2-inch diameter pipe with a length of 62 meter. Details of the adjustable by-pass and electronic equipment of the in-house fabricated pig will be presented. The paper is built up as follows. In section 2 the experimental setup used to perform the experiments is described. In addition, the design of the speed controlled pig will be presented. The control mechanism makes use of data gathered by a pressure sensor and an accelerometer which are installed on the pig. Section 3 contains results on the characterization of the pressure loss coefficient of the pig. Furthermore, the experimental results with an active control mechanism of the pig are presented. Section 4 concludes this study and discusses possibilities for future research.

2 EXPERIMENTAL SETUP

The experimental setup consists of a 62 m long pipe made of transparent PMMA, see Figure 1. The inner diameter of the pipe is 52 mm. The working fluid is air, which is tapped from a central system which is kept at 8 bara. Before the air enters the pipe, the pressure is reduced to 2 bara and flows through a gas flow controller (Bronkhorst – MASS-STREAM Series D-6300). The flow controller allows the mass flow of air to be controlled and monitored. The outlet pressure is atmospheric.

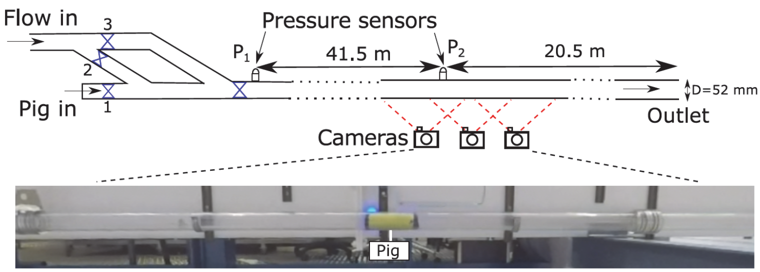
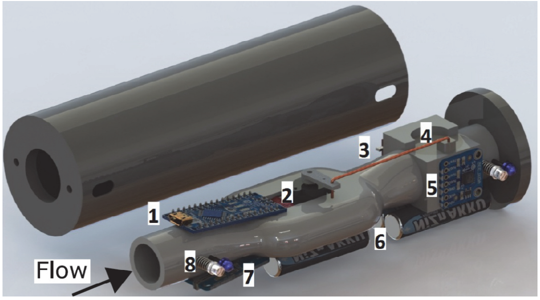


Figure 1: Experimental setup.

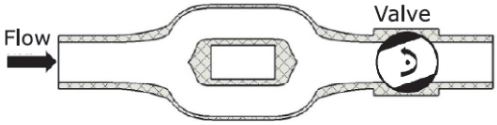
A pig launcher is located at the inlet of the pipe through which a pig can be inserted into the pipe. The procedure is as follows. When the pipe is operating in steady state, valve 3 is opened while valve 1 and valve 2 are closed (see Figure 1). Valve 1 can subsequently be opened to insert a pig into the launcher. After closing valve 1, the flow can now be redirected through the pig launcher by opening valve 2 and closing valve 3. The pig will now be launched into the pipe. The pipe is equipped with two pressure sensors P1 and P2 (Validyne DP15), see Figure 1. In addition, three high speed cameras (GoPro HERO 4) are mounted approximately 42 m downstream, which allow the local dynamics of the pig to be analyzed.

A detailed drawing of the speed controlled pig which is used in the experiments is given in Figure 2a. The length of the pig is 167 mm and the total mass is 0.178 kg. Various electronic components are installed which are connected to one central microcontroller (Arduino Nano).

The by-pass area can be adjusted through a rotating valve which is actuated by a servomotor (Spektrum SPMSA3030). A close up of the by-pass area reveals that the central by-pass splits into two tubes around the servomotor which rejoin before the rotating valve, see Figure 2b. The reason is that the servomotor only fits in the centre of the 52 mm diameter speed controlled pig, and as a consequence the by-pass had to be redirected around the servomotor. An accelerometer measures the acceleration of the pig, which gives valuable information of possible speed excursions of the pig. In addition, a pressure sensor (NXP - MPXV5050GP) is mounted on the pig which measures the pressure at the back of the pig (not shown in Figure 2a). A schematic which shows how the various components including the pressure sensor are connected to the Arduino is shown in Figure 2c. A SD-card slot allows data that is measured during a pigging run to be logged onto a SD-card. The logged data, such as pressure and acceleration, can then be read and analyzed after the pigging run is completed.



(a)



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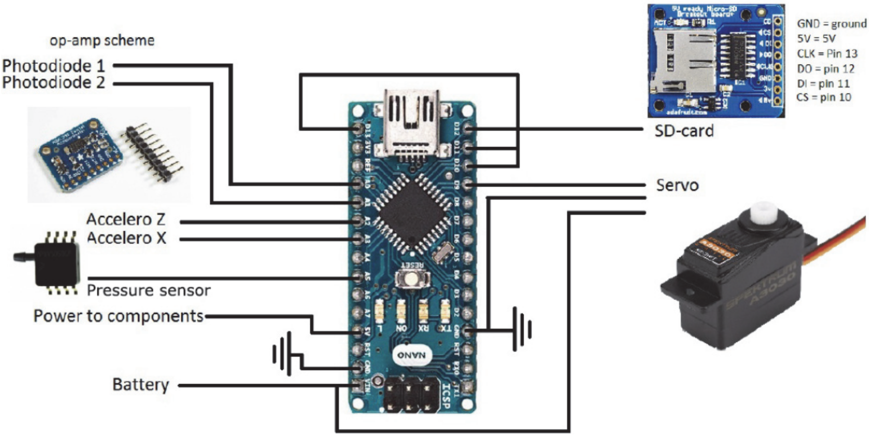


(c)

Figure 2: (a) 3D impression of the speed controlled pig: [1] Arduino Nano, [2] Servo, [3] On/off switch, [4] Valve, [5] Accelerometer, [6] Batteries, [7] SD slot, [8] LEDs and photodiode. (b) Close-up of the by-pass region including the rotating valve mechanism. (c) Connection of various components to the Arduino Nano.

The position of the rotating valve determines the by-pass area A_h, see Figure 3. This area is defined as the projected area that is created by the overlap of two circles, see Figure 3b. This figure shows the side view of the by-pass area with axial direction out of plane. Here the solid circle represents the by-pass area when the valve is fully opened, which is denoted as A_0. The position of the dashed circle is determined by the position of the valve. The opening distance between the valve and the wall of the by-pass is denoted as H and can be expressed as:

$$H = r + R_v \cos\left(\alpha + \cos^{-1}\left(\frac{r}{R_v}\right)\right). \qquad (1)$$

Here R_v is the radius of the rotating valve, α is the opening angle of the valve and r is the radius of the by-pass tube. The by-pass area A_h can now be expressed as:

$$A_h = 2\left[\frac{\gamma}{2\pi}\pi r^2 - \left(r - \frac{H}{2}\right)\left(r \sin\frac{\gamma}{2}\right)\right]. \qquad (2)$$

Here γ is defined as:

$$\gamma = 2\cos^{-1}\left(1 - \frac{H}{2r}\right). \qquad (3)$$

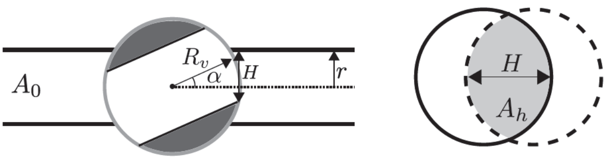


Figure 3: Details of the by-pass valve. (a) Top view. (b) Side view.

3 RESULTS

In this section results obtained with the speed controlled pig are presented. First, the pressure loss coefficient of the pig is characterized experimentally, see Section 3.1. The experimental results are compared with a correlation which is applicable to the shape of the by-pass area. Subsequently, Section 3.2 presents experimental results which have been gathered during the performed pigging runs.

3.1 Characterization of the pressure loss coefficient

The pressure drop Δp over a by-pass pig is usually characterized by a dimensionless pressure loss coefficient K, which is defined as:

$$K = \frac{\Delta p}{0.5\rho U_{bp}^2}. \qquad (4)$$

Here ρ is the density of the by-passing fluid and U_{bp} is the fluid velocity in the by-pass. In order to characterize the behaviour of the speed controlled pig the pressure loss coefficient K was measured. The pressure loss coefficient K is measured by fixing the pig inside the pipeline between two pressure sensors. The Arduino was used to control the position of the valve in order to create different by-pass area fractions A_h/A_0, as was described in the previous section. The pressure loss Δp and pressure loss coefficient K are subsequently determined for three different upstream bulk flow velocities: 1, 2, and 3 m/s. The result is shown in Figure 4.

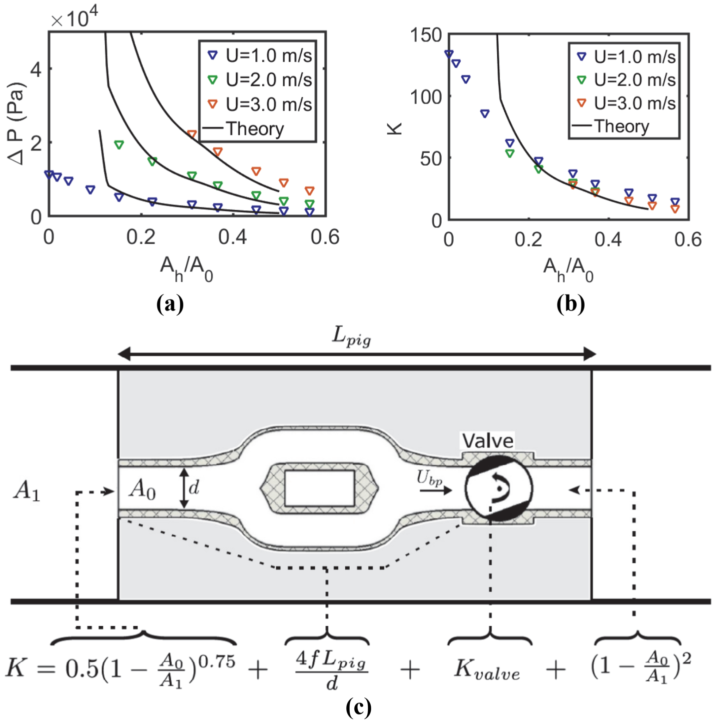


Figure 4: (a) Pressure drop (b) Pressure loss coefficient. (c) Geometrical breakdown of different contributions to the pressure loss coefficient.

The pressure loss coefficient of a by-pass pig has been previously successfully modelled as the pressure loss of a thick orifice [1], provided the shape of the by-pass pig resembles a thick orifice. For by-pass areas which are shaped in a different way, alternative correlations have been proposed and verified by CFD simulations [2,3]. These alternative correlations rely on a geometrical decomposition of the by-pass geometry and formulate a loss coefficient which takes into account the contribution of the various geometrical building blocks [3,4] of which the by-pass pig consists. We now apply this procedure to the geometry of the speed controlled pig of the current research. We assume that the geometry can be regarded as a combination of a thick orifice and a rotating valve, see Figure 4c. We then obtain the following equation for K:

$$K = 0.5\left(1 - \frac{A_0}{A_1}\right)^{0.75} + \frac{4fL_{pig}}{d} + K_{valve} + \left(1 - \frac{A_0}{A_1}\right)^2. \quad (5)$$

Here A_1 is the pipe area, A_0 is the by-pass area of the tube, d is the diameter of the by-pass tube, f is the Fanning friction coefficient (which we calculate using the Churchill correlation) and K_{valve} is the contribution of the rotating valve. We note that without this contribution equation (5) is equal to the correlation for a thick orifice [5]. It now remains to describe K_{valve}. This geometry has been characterized and tabulated by Idelchik [5]. Table 1 reproduces this result. We adopt this table to describe K_{valve} and use cubic spline interpolation to obtain values which are in between the listed values for A_h/A_0.

Table 1: Loss coefficient K_{valve} according to Idelchik [5].

A_h/A_0	0.93	0.85	0.69	0.52	0.35	0.13	0.11	0
K_{valve}	0.05	0.31	1.84	6.15	20.7	95.3	275	N.A.

As shown in Figure 4, there is good agreement between the prediction with equation (5) for K (as shown by the black lines) and the experimental results for various values of the by-pass velocity. We note that for small by-pass ratios the experimental results start to deviate from the predictions. This could be caused by a small leakage of the rotating valve, which is not completely air tight, even not in fully closed position because there is a small space which allows the valve to rotate. In addition, we emphasise that the characterization of K_{valve} by Idelchik is not accurate enough for small by-pass areas. As a final remark we note that the velocity U_{bp} which is used here to normalize the pressure drop is the velocity defined in the by-pass tube. The highest velocity which occurs in the system, however, occurs in the smallest by-pass area which is located in the rotating valve. If this velocity would be used to normalize the pressure drop, the values of K would be closer to one. Here, however, we adopt the convention that Idelchik [5] uses.

3.2 Pigging runs

Figure 5 shows typical pressure data which are obtained during a pigging run. The pressure which is recorded by the sensor on the pig is shown by the black line. As is explained in Section 2, the sensor measures the pressure at the back of the pig. At around 28 s the pressure behind the pig suddenly increases, which coincides with the moment of launching the pig. Quickly thereafter the pressure at the upstream pressure sensor P1 (see Figure 1) increases at the moment that the pig reaches P1. We note that the signal which is recorded on the pig closely follows the P1 signal. At around 74 s the signal of P2 takes up, which corresponds to the pig arriving at P2. At 96 s the pig is trapped and the flow returns to steady state flow conditions. The lower panel of Figure 5 shows a close up of the signal between 80 s and 92 s. Here it can be seen that the signals of P1 and P2, and the pressure as measured on the pig are very similar even though the locations where the pressure is measured differ. The reason is that losses due to friction of the fluid with the pipe wall are in this case negligible compared to the friction of the pig with the pipe wall.

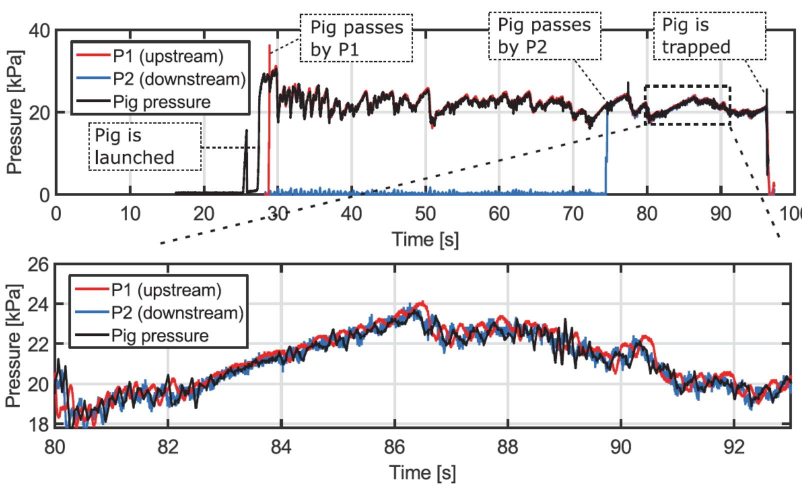
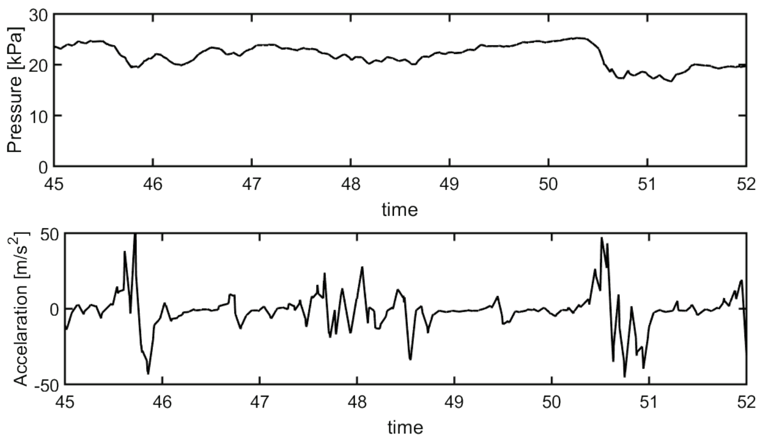
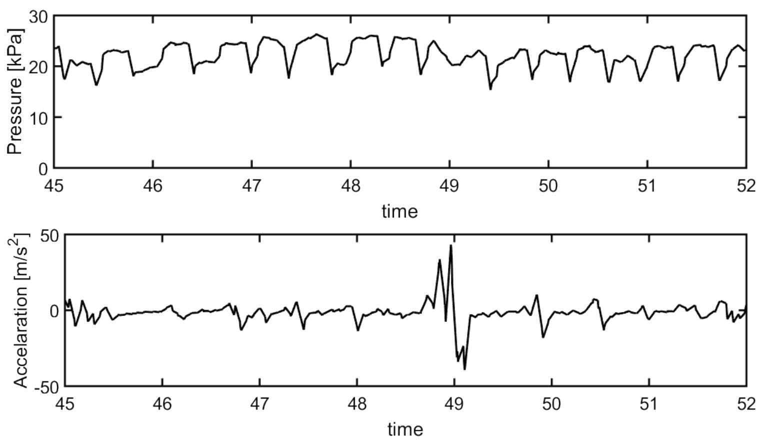


Figure 5: Pressure data. The lower graph shows a close-up of the signal indicated by the box in the upper graph.

From the pressure in Figure 5, it can be deducted that an average driving pressure of 22.0 kPa is needed to move the pig. With the cross section of the pig being equal to 0.0021 m^2, this corresponds to an average friction force of the pig with the pipe wall of 46.7 N. The fact that the driving pressure force is not constant but instead shows oscillations is due to unsteady motion of the pig through the pipeline. Small variations in the pipe diameter or irregularities in the pipe wall may cause an increase in friction which slows down the pig. The gas pressure behind the pig then builds up during this period of increased friction which will eventually accelerate the pig. When the friction returns to a lower value, the increased pressure behind the pig will result in an overshoot in the pig velocity, as is explained in Section 1. This oscillatory motion, which can even manifest itself as stick-slip motion, has indeed been observed on the video recordings. We now would like to reduce this pig velocity overshoot by means of actively controlling the by-pass area. Figure 6a shows the pressure data as well as the data which are collected from the accelerometer from a test run without any by-pass regulation. The by-pass is in a fully closed position. The acceleration data show large peaks which is a signature of the unsteady pig velocity.



(a)



(b)

Figure 6: Pressure and acceleration data from (a) an uncontrolled run, (b) a controlled run.

The data from this run have been used to design an algorithm which looks for pressure build-ups and waits for the moment that the acceleration exceeds a certain value. The by-pass valve is then opened for a certain amount of time before closing it again. The idea is that opening the by-pass valve will allow the excess pressure behind to pig to be released such that the pig will not accelerate as much it would without this regulation, thereby preventing a next stick-slip cycle.

The algorithm consists of three states. The first one makes sure that the by-pass is in a closed position. Subsequently it checks if the pressure is above a certain value, here set to 18 kPa. If this is the case the current acceleration value is saved and the second state is entered. In the second state it is checked whether the saved acceleration in state one increases by a preset amount, set to 2 m/s^2. If this is the case the valve opens for a fixed amount of time, here set to 0.4 s. The result is shown in Figure 6b. As expected the pressure stays controlled between certain boundaries, and the peaks of the acceleration are decreased for this test run. We note that the values which have been used are case specific and applicable to the current conditions. It is important to note that this algorithm may actually cause more stick-slip behaviour if the parameters are not chosen correctly. If, for example, the duration of the valve opening is too long, the driving pressure decreases too much, which can result in stick-slip motion. A more autonomous control algorithm is thus recommended, and future test runs are being planned.

4 CONCLUSIONS

A speed controlled pig has been designed and custom made for pigging experiments in a 52 mm diameter pipe with a length of 62 m using air as working fluid. The pig is able to log the pressure as measured at the back of the pig as well as the acceleration which can be read out after a pigging run is completed. An adjustable rotatable valve was installed which provides a means to actively control the by-pass area. The pressure drop as function of the opening of the by-pass valve has been measured for three bulk velocities and has been characterized by a correlation for the pressure loss coefficient. The experiments showed that the measured pressure data in combination with the acceleration data can be used to reduce velocity excursions of a pig in a low pressure pipeline by actively controlling the by-pass area. The presented and tested algorithm, however, is still case specific and it is therefore recommended to develop a more general solution to limit velocity excursions of pigs in low pressure pipelines. In addition, the effect of multiphase flow on the dynamics of a speed controlled pig in low pressure systems must be investigated. At the moment the setup is operated in two phase (air-water) and the results are currently being analyzed.

ACKNOWLEDGMENTS

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