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Experiments and modeling of by-pass pigging under low-pressure conditions

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ABSTRACT

We present experimental and numerical results for by-pass pigging under low-pressure conditions which aided the design of a speed-controlled pig (Pipeline Inspection Gauge). Our study was carried out using air as working fluid at atmospheric pressure in a 52 mm diameter pipe of 62 m length. The experimental results have been used to validate simplified 1D models commonly used in the oil and gas industry to model transient pig behaviour. Due to the low pressure conditions oscillatory behavior is observed in the pig speed, which results in high pig velocity excursions. The oscillatory motion is described with a simplified model which is used to design a simple controller aimed at minimizing these oscillations. The controller relies on dynamically adjusting the by-pass area, which allows to release part of the excess pressure which builds up in the gas pocket upstream of the pig when the motion of the pig is arrested. Subsequently, the control algorithm is tested by a 1D transient numerical model and it was shown to successfully reduce the pig velocity excursions.

1. Introduction

Pipelines are used in many industries as a means of transporting fluids. Such fluids can consist of gases, liquids, or combinations of gases, liquids and solids. An inevitable consequence is the internal maintenance of those pipelines. In the oil and gas industry this is done by using a pig (Pipeline Inspection Gauge). This is a cylindrical device which travels through the pipeline driven by the fluid flow, see for example Fig. 1. Pigs have a wide range of applicability, including cleaning the inside of a pipeline, removing excessive liquid from a liquid-gas pipeline, or distribution of corrosion inhibitor [1–4]. Pigs can also be equipped with intelligent sensors which can inspect the inner pipe wall [5], for example. There is a wide variety of pigs to perform these tasks. An example of three common utility pigs are (1) the mandrel pig, (2) the solid cast pig and (3) the foam pig, which are shown in Fig. 1 [1]. A mandrel pig consists of a metal core with elements mounted on this core. It depends on the purpose of the pigging operation which elements are mounted. Typical elements are scrapers for cleaning, guiding discs to ensure a proper alignment with the pipe and sealing elements to seal the pipe. These elements are normally made from polyurethane. A solid cast pig differs from a mandrel pig in the sense that it is made out of one material, often also polyurethane. A foam pig is made of softer material and has a larger volume. The pigging purpose and the costs determine which of the types is most appropriate to perform a pigging operation.

It is desirable that the product flow, which is driving the pigs through the pipeline, is interrupted as little as possible during the pigging operation. Conventional pigs, such as the ones displayed in Fig. 1a–c, typically completely seal the pipeline. As a consequence the speed of the device will be equal to the velocity of the product flow. However, often a lower travel speed is desired, as a too high pig velocity may damage the pig or pipeline. In addition, it has been shown that a lower pig velocity is also beneficial for the cleaning and inspection performance of the pig [3,7]. A solution to achieve a lower pig velocity while avoiding production deferment is the use of a by-pass pig, which does not seal the complete pipeline. Instead, a by-pass pig has a hole, or by-pass area, which allows fluid to by-pass the pig while it is moving inside the pipeline, see Fig. 1d. The presence of a by-pass will cause that the pig velocity is not dictated by the velocity of the product flow. Instead the pig velocity will be lower and it is now determined from a balance between the driving pressure force and the friction force between the pig and the pipe wall [8]. The risk, however, of using a by-pass pig is that the driving force on the pig becomes too low to overcome the wall friction force, which will result in a pig being stuck in the pipeline. To mitigate

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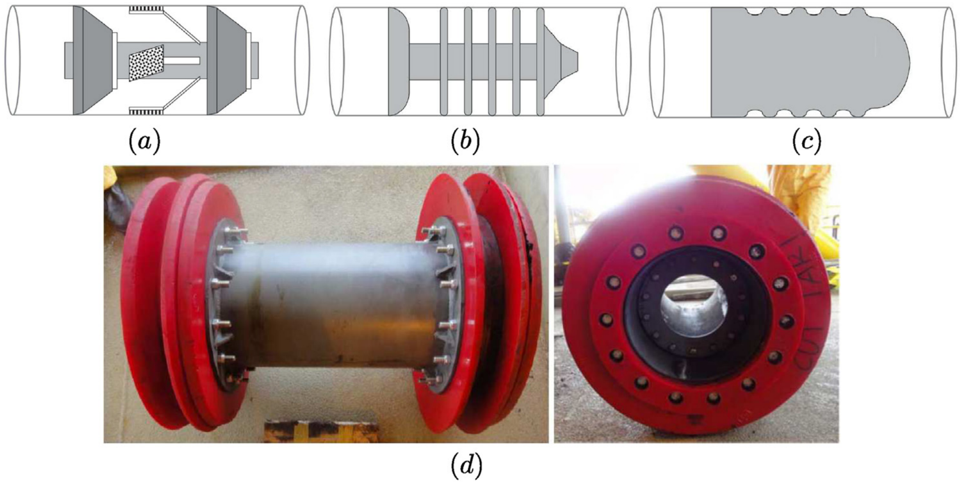

Fig. 1. Several pig types: (a) Mandrel pig. (b) Solid cast pig. (c) Foam pig. (d) By-pass pig. Adapted from [1,6].

the risk of a stuck pig, so-called speed controlled pigs have been designed which have an adjustable by-pass area which provides the right amount of by-pass such that the velocity of the pig is lowered, while the pig does not get stuck [7]. Detailed mechanisms on how such a control system should be designed are only scarcely found in literature [9,10].

In this paper we consider the movement of a pig in a low pressure gas-filled pipeline. Pigging of such low pressure gas-filled pipelines in actual field operation can lead to large oscillations in the pig velocity due to the compressibility of the gas, see for example [11,12]. This is because compressed gas pockets may build up at the upstream side of the pig when it is moving slower due to locally increased friction caused by for example irregularities in the inner pipe diameter. When the pressure in such a pocket has been sufficiently built-up, it is able to catapult the pig, resulting in large pig velocity excursions. This can lead to an unsafe and inefficient pigging operation. The effect described above gets more pronounced when the operating pressure or the flow velocity in the pipe is low. It can even result in a so-called 'stick-slip motion', where the pig slows down completely after a period of high velocity. This stick-slip motion of the pig is generally undesired in the industry. However, when a pig is equipped with appropriate speed control, the occurrence of high pig velocities in low pressure gas filled pipelines may be suppressed, which enables safe and effective pigging of these pipelines.

This paper is built up as follows. In Section 2 we first discuss the force balance on a (by-pass) pig. In addition we derive a simplified model which describes the motion of a pig in a low pressure system. The simplified model gives insights into the basic physical mechanisms which are key to unsteady pig motion due to low pressure conditions in gas filled pipelines. The simplified model relies on some assumptions, most notably the assumption that the pressure upstream of the pig is directly determined by the volume that the gas occupies upstream of the pig. In reality the pressure upstream of the pig will change as result of a transient pressure wave, rather than a instantaneous response to the change in volume. We therefore also include a more complete approach which models the motion of the pig in a transient 1D pipe model. In Section 3 we describe the experimental setup that has been used to perform pigging experiments. The experimental setup has been used in a previous work to test a prototype of a speed controlled pig [13,14]. In this work we more systematically study the behaviour of by-pass pigs with constant by-pass area which, in combination with the developed models, is expected to improve the design of such a speed controlled pig. In Section 4 a comparison will be made between the experimental results and the various models. The proposed models and experiments are subsequently used for the design of a PD controller in order to reduce pig velocity excursions through dynamically adjusting the size of the by-pass. Section 5 gives conclusions and discusses possibilities for future research.

2. Models

Whereas the pig velocity U_{pig} of a conventional pig in a pipeline is dictated by the bulk velocity U upstream of the pig, the pig velocity of a by-pass pig will be lower because part of the fluid is able to flow through the by-pass pig, see Fig. 2.

The motion of a by-pass pig in a horizontal pipeline is determined from a force balance between the driving pressure force F_p and frictional force F_{fric}. By applying a control volume analysis over the whole pig (including the by-pass area), F_p can be expressed as $F_p = \Delta p\, A$ where Δp is the pressure drop over the pig and A is the pipe cross-sectional area. The pressure drop is usually characterized by a pressure loss coefficient K defined as [15]:

$$K = \frac{\Delta p}{\frac{1}{2}\rho_{bp} U_{bp}^2}. \tag{1}$$

Here ρ_{bp} is the density of the fluid in the by-pass (which is taken as the density downstream of the pig) and U_{bp} is defined as the fluid velocity in the by-pass region taken relative to the pig velocity, see [16,8]. A mass balance taking into account a higher density upstream of the pig ρ_{up} due to compressibility of the fluid thus yields the following expression for U_{bp}:

$$U_{bp} = \frac{D^2}{d^2}\frac{\rho_{up}}{\rho_{bp}}(U - U_{pig}). \tag{2}$$

Here D is the pipe diameter and d the diameter of the by-pass hole. Substituting this expression for U_{bp} into Eq. (1) and applying a steady state force balance on the pig ($\Delta p\, A = F_{fric}$) results in an equation for the velocity of the by-pass pig [8,17]:

$$U_{pig} = U - \frac{d^2}{D^2}\frac{\rho_{bp}}{\rho_{up}}\sqrt{\frac{F_{fric}}{K\frac{1}{2}\rho_{bp}A}}. \tag{3}$$

When the by-pass area fraction d^2/D^2 goes to zero, Eq. (3) returns a pig velocity equal to the bulk velocity, as is the case for a conventional pig. When d^2/D^2 is not equal to zero, detailed knowledge of both K and F_{fric} are needed in order to accurately predict the pig velocity. The pig geometry in this research can be regarded as a