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Frictional forces for disc-type pigging of pipelines

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ABSTRACT

We investigate the frictional force which is acting on a pipeline pig. Two complementary experimental setups have been designed and used to study the sealing disc of a pig, which is responsible for the frictional force between the pig and the pipe wall. Six 12′′ off the shelf sealing discs from two different vendors have been used. The first setup is a static setup in which the sealing disc is subjected to a normal wall force and a tangential friction force. A unique feature of the setup is that the ratio between the friction force and the wall force can be readily adjusted. This allows to experimentally determine the force ratio which is directly related to the Coulomb friction coefficient, which is often a difficult parameter to predict. Furthermore, the static setup is used to systematically study the effect of oversize, thickness, and Young's modulus of the sealing disc on the frictional force. A direct comparison with Finite Element (FE) calculations is made. The second experimental facility consist of a dynamic setup in which a sealing disc is pulled through a vertical 1.7 m long pipe. The effect of possible lubrication on the frictional force is studied by applying water to the sliding contact and comparing the results with dry pull tests for different sliding velocities. The corresponding difference in the Coulomb friction coefficient was quantified using FE calculations which were successfully verified with the static setup. The sensitivity of possible wear of the sealing disc on the frictional force is discussed.

1. Introduction

Pipelines that are used for the transport of fluids represent significant costs and need regular maintenance (Rui et al., 2017, 2018). In the oil and gas industry this is usually done by sending so-called pigs through the pipeline, see Fig. 1a. Such a pig travels along with the production fluids through the pipe and can serve multiple maintenance purposes. For example pigs are used to remove wax particles that may have been deposited at the pipe wall (Wang et al., 2008; Tan et al., 2014; Quarini and Shire, 2007; White et al., 2017) or to sweep out unwanted liquid accumulation in a pipeline that is used for multiphase gas-liquid transport (Wu and van Spronsen, 2005; Entaban et al., 2013). Apart from cleaning purposes, pigs can be equipped with sensors which inspect the condition of the pipe wall. This is also referred to as intelligent pigging (Quarini and Shire, 2007; Money et al., 2012). For a detailed overview of pigging applications and pig types, the reader is referred to (Cordell and Vanzant, 2003; Tiratsoo, 1992). In any case the pig is driven by the production fluids which are transported through the pipeline. This means that the pressure difference that is generated over the pig has to overcome the frictional force between the pig and the pipe wall. To ensure a safe and effective pigging operation it is thus required to know the frictional force in order to prevent too high pressures in the system.

A conventional pig completely seals the pipeline with a flexible sealing disc, see Fig. 1. The radius of the sealing disc usually has an oversize compared to the inner pipe radius, which ensures a tight seal between the pig and the pipe wall. The travel velocity of a conventional pig through a pipeline is therefore equal to the mixture velocity of the upstream fluids. In some cases it is desired to lower the travel velocity of the pig, as it may cause damage to the pipeline or the pig itself. Also for cleaning, liquid removal, and inspection purposes it is beneficial to reduce the pig velocity (Wu and van Spronsen, 2005; Money et al., 2012; Tolmasquim and Nieckele, 2008; Carvalho and Rotava, 2017). A solution to achieve a lower pig velocity without causing production loss is the use of by-pass pigs (Wu and van Spronsen, 2005). By-pass pigs have a by-pass hole which allows the production fluids to flow through the pig. As a result the pig velocity is not dictated by the upstream mixture velocity anymore, but is, in a horizontal pipe, determined by a balance of the by-passing fluid force and the frictional force of the pig with the pipe wall. The force on a by-pass pig due to the by-passing fluids has been previously studied for various by-pass pig configurations, see (Singh and Henkes, 2012; Hendrix et al., 2017). The main

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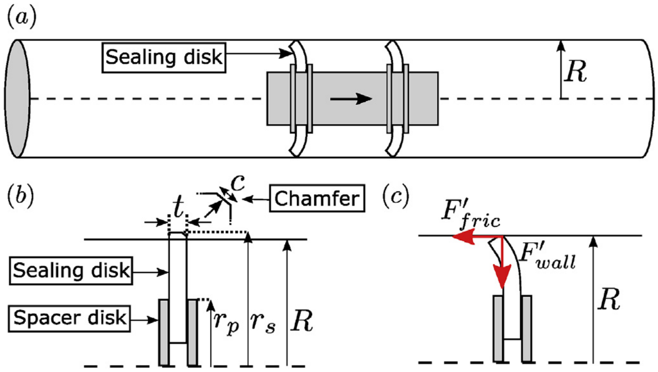

Fig. 1. (a) A pig travelling inside a pipeline (b) Undeformed sealing disk. (c) Deformed sealing disk.

focus of the current paper is on the frictional forces which are encountered during pipeline pigging. As the pig contacts the pipe wall through the sealing disc, the effect of the properties of the sealing disc on the frictional force are of interest. The external force of the pipe wall on the sealing disc is distributed along the circumference and has unit Newton per meter circumference. The distributed force can be decomposed in a distributed friction force (F'_{fric}) oriented parallel to the direction of movement of the pig and a distributed wall normal force (F'_{wall}), see Fig. 1c. At the onset of sliding the ratio of these two distributed forces gives the local Coulomb friction coefficient.

Almost no models are available to estimate the frictional force during pipeline pigging: predictions often rely on empirical findings and field experience (Cordell, 1992; Esmaeilzadeh et al., 2009). For example Cordell (1992) presents a diagram in which the driving pressure that is needed to overcome the frictional force is solely dependent on what type of pig is used (e.g. a cleaning pig versus an inspection pig). However, no information on the geometrical or material properties of the sealing disc is present in this approach. O'Donoghue (1996) presents a simplified model which does include geometrical and material properties of the sealing disc into a friction model. This model assumes that the deformed sealing disc adopts the shape of an circular arc and subsequently evaluates the internal stresses in the sealing disc which can be used to predict the frictional force. Despite that the model contains more physics than for example Cordell's model, it is known to systematically underpredict the friction force (O'Donoghue, 1996; Hendrix et al., 2016). Rather than relying on a simplified model, another approach is to perform a full Finite Element (FE) calculation of the sealing disc, which has recently been undertaken in (Zhu et al., 2015a, 2015b). Clearly, an axisymmetric 2D or even full 3D FE approach has the advantage that it contains more physics than for example a simplified axisymmetric 1D approach, such as for example the model of O'Donoghue (1996). On the other hand, it is more difficult to embed case specific FE calculations in already existing tools.

Two types of laboratory approaches to experimentally study the frictional force of a sealing disc have been found in the literature. One approach consists of a pull test in which a sealing disc/pig is pulled through a pipe while monitoring the pulling force (Zhu et al., 2015b, 2017). An advantage is that in steady state motion this pull force can be directly related to the friction force. A disadvantage is that the wall normal force is not directly measured, and therefore the Coulomb friction coefficient is unknown. Another approach relies on fixating the sealing disc while pressing it against a rotating steel plate which mimics the pipe wall, see (Tan et al., 2015) in which this setup was used to study wax removal from a pipe wall. Such a setup can be used as a tribometer in which the load and friction force can be simultaneously measured which enables to measure the friction coefficient for various contacts (Tan et al., 2013; Lan et al., 2017). While the Coulomb friction coefficient can be carefully characterized with such a setup, a disadvantage is that the friction force of a sealing disc in a confining pipe geometry is not directly measured.

In the present research a static experimental setup is presented which is used to simultaneously measure the friction force and the wall normal force acting on a sealing disc in a confining pipe geometry. The static setup is a modified and improved version of the setup described in (Hendrix et al., 2016), which will be explained in the Section 2. Six 12" off the shelf sealing discs from two different vendors have been used in the experiment. A flexible hull is wrapped around the sealing disc and F'_{wall} is subsequently generated by reducing the diameter of that hull. F'_{fric} is generated by pulling the disc in the axial direction. The forces are recorded in static equilibrium. The forces that are applied in static equilibrium are the same as for a sealing disc that moves in steady state motion through a pipeline. By changing the force ratio between the friction force and the wall force the Coulomb friction coefficient which would apply to a sealing disc which moves at steady state is thus mimicked. The experimental setup thus allows to study the effect of the friction coefficient which is difficult to study in a dynamic experiment in which a sealing disc is pulled through a pipe and the wall force is generally unknown. The results from the static setup, which is referred to as static pig pull facility, are captured by 2D axisymmetric FE calculations for which appropriate boundary conditions are formulated. A detailed comparison is made for both the involved forces as well as the shape of the deformed sealing disc. Apart from the friction coefficient, the effect of the oversize, the thickness, and the Young's modulus of the sealing disc on the friction force are investigated.

Next to the static pig pull facility, a new dynamic pig pull experiment is designed which is used to present a case example of how the results of the static pig pull facility can be related to a dynamic pull test. In this dynamic experiment the sealing disc is pulled through a 1.7 m vertical pipe while monitoring the pull force. The effect of possible lubrication by applying water at the sliding contact is investigated. The difference in friction coefficient between a dry and wet contact is quantified.

The outline of the paper is as follows. In Section 2 the experimental setup of the static and the dynamic pig pull facility and the applied measurement procedure are explained. At the end of the section the numerical setup for the FE calculations and the applied boundary conditions are discussed. Section 3 presents the results from the static pig pull facility and a direct comparison with the FE calculations is made. Subsequently the results from the dynamic pig pull facility are presented and linked to the results of the static experiments. Section 4 concludes and discusses possibilities for future research.

2. Methods

Inspecting Fig. 1b we can identify two dimensionless numbers pertaining to the undeformed geometry of the sealing disk. There is a dimensionless thickness t' and a dimensionless clamping ratio r_p', which are defined as:

$$t' = \frac{t}{r_s - r_p} \tag{1}$$

$$r_p' = \frac{r_p}{r_s} \tag{2}$$

Here t is the thickness of the sealing disc, r_s is the outer radius of the sealing disc, and r_p is radius of the spacer discs which are used to attach the sealing disc to pig body. A third geometrical dimensionless number could take the presence of a possible chamfer into account, see Fig. 1b. The dimensionless chamfer height can be for instance defined as $c' = c/t$, where c is the length of the chamfer which is for simplicity assumed to be under an angle of 45°. The effect of a variation in chamfer size is discussed in Section 3.4. Two additional dimensionless numbers can be introduced for the sealing disk which is deformed due to the confinement of the pipe wall, see Fig. 1c. We define the oversize parameter Δ and the force ratio μ as follows: