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Characterization of the pressure loss coefficient using a building block approach with application to by-pass pigs

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A B S T R A C T

A building block strategy for modelling the pressure loss coefficient of flow through a complex geometry is presented. The approach relies on decomposing a complex flow geometry into geometrical building blocks of which the pressure loss coefficients are characterized individually. The different contributions are subsequently combined to describe the pressure loss of the geometry as a whole. This approach is applied and tested to an industrially relevant application: a by-pass pig (Pipeline Inspection Gauge). This is a cylindrical device that travels inside a pipeline and is commonly used in the oil and gas industry for pipeline maintenance. An important factor in determining the ultimate velocity of the device is the pressure drop over the by-pass pig, which is characterized by a pressure loss coefficient due to the by-passing fluids. In this study the pressure loss coefficient of three frequently used by-pass pig geometries in a single phase pipeline is investigated with Computational Fluid Dynamics (CFD). The CFD results are used to validate the simple building block approach for systematic modelling of the pressure loss through the by-pass pigs, which takes the geometry and size of the by-pass opening into account. It is shown that the pressure loss models can capture the CFD results for each of the three pig geometries. The pressure loss models can be combined with pig/pipe-wall friction models to predict the velocity of a by-pass pig in a single phase pipeline, which is important for a safe and effective pigging operation. The applied building block approach may also be suitable to characterize pressure loss coefficients of complex geometries in general.

1. Introduction

In the oil and gas industry, pipeline networks are used to transport production fluids from wells to production plants. During normal operation, these pipelines need regular cleaning and inspection. Ideally, this pipeline maintenance should interrupt the production as little as possible. Typically, pipeline maintenance is done with a pig (Pipeline Inspection Gauge). This is a cylindrical or spherical device that is launched at the inlet of the pipe and subsequently travels through the pipeline while being propelled by the production of fluids. The pig is trapped in a receiver at the end of the pipeline. While a conventional pig completely seals the pipeline and travels with the same velocity as the production fluids, a by-pass pig has an opening hole which allows the production fluids to partially flow through the pig body. Fig. 1a shows an example of a by-pass pig. A by-pass pig will typically travel with a lower pig velocity compared to a conventional pig that completely seals the pipeline, as the velocity of the by-pass pig is not dictated by the velocity of the production fluids anymore, but depends on the overall force balance for the pig. In steady state this means that the driving pressure force F_p of the production fluids balances with the frictional force F_{fric} of the pig with the pipe wall, see Fig. 1b. The driving pressure force F_p depends on the pressure drop Δp over the pig and is expressed as $F_p = \Delta p A_{pig}$, where A_{pig} is the frontal area of the pig (which is equal to the cross sectional area of the pipe).

The reduction of the pig velocity has proven to be beneficial for both inspection and cleaning purposes (Wu and van Spronsen, 2005; Money et al., 2012). In addition, a lower pig velocity is necessary for safe operation, as a too high pig velocity may damage the insides of the pipe or the pig itself. As the travel velocity of the by-pass pig is important for the efficiency and safety of the pigging operation, detailed knowledge of the pressure drop Δp over the pig is needed in order to predict its velocity. This study focuses on quantifying the pressure drop Δp over various types of by-pass pigs which is characterized by a pressure loss coefficient K, defined as:

$$K = \frac{\Delta P}{\frac{1}{2}\rho U_{bp}^2}, \qquad (1)$$

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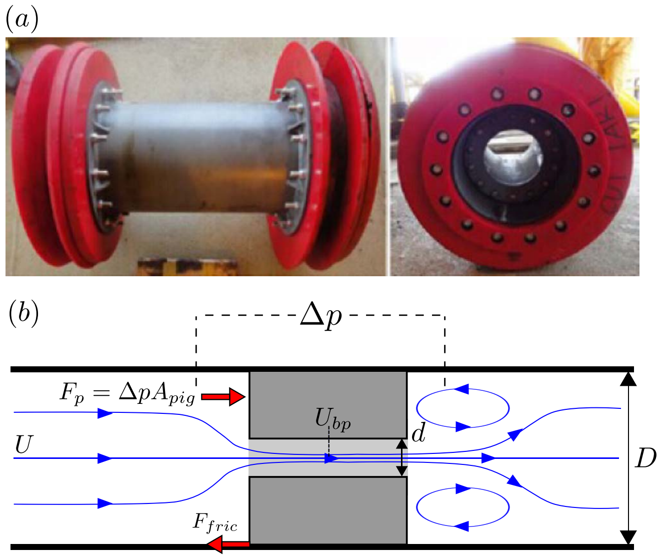

Fig. 1. (a) A bi-directional by-pass pig, taken from Lee et al. (2012). (b) A schematic of the forces on a by-pass pig in a horizontal pipeline. In steady state the driving force F_p due to the by-passing fluids is balanced by the frictional force F_{fric} of the pig with the pipe wall. In this schematic D indicates the pipe diameter, d the diameter of the by-pass hole, U the upstream bulk velocity, and U_{pig} the pig velocity.

where ρ is the density of the fluid and U_{bp} is the fluid velocity in the horizontal by-pass region relative to the pig motion, see Fig. 1. The pressure loss coefficient K depends on the size of the by-pass opening as well as on the design of the by-pass geometry, which may vary depending on the application of the pig. A good description of K is not only important for a steady state calculation of the pig velocity, but is also a relevant input parameter for 1D transient tools. Examples include 1D codes which are described in Nieckele et al. (2001), Tolmasquim and Nieckele (2008), Esmaeilzadeh et al. (2009), Jamshidi and Sarkari (2016) and commercial tools such as OLGA (Bendiksen et al., 1991) or LedaFlow (Goldszal et al., 2007), which are commonly used in the oil and gas industry. In these transient tools the trajectory of the pig through a pipeline can be monitored, and a relation for K needs to be known in advance. So far reliable correlations for K are missing, and the present study is aimed at providing one.

As the geometry of a pig varies depending on its application, a building block approach is used in order to provide a general framework for determining the corresponding pressure loss coefficient. The building block approach relies on a geometrical decomposition of the by-pass pig, and accounts for the contribution of the individual components of the by-pass pig geometry to the overall pressure loss. It is thus assumed that the flow patterns are uncorrelated between building blocks, i.e. the local flow pattern within a building block depends solely on geometrical characteristics of that building block. In order to validate the building block approach a CFD (Computational Fluid Dynamics) approach is applied to model fully turbulent single phase flow through various types of by-pass pigs. The bulk Reynolds number is fixed at $Re = UD/\nu = 10^7$, where ν is the kinematic viscosity of the fluid, U is the average velocity, and D is the pipe diameter. A similar Reynolds number has been used in a previous CFD study on by-pass pigs (Singh and Henkes, 2012), which allows for a direct comparison of the new results obtained in this work. From the CFD results the pressure loss coefficient K can be extracted.

The building block approach is tested on three different by-pass pig geometries encountered in the industry. First the relatively simple design of the bi-directional by-pass pig is revisited, which is shown in Fig. 1a. Furthermore, the by-pass pig shown in Fig. 2a is considered, which is referred to as the disk pig. This pig has a deflector plate, or disk, added at the exit of the by-pass pig. The deflector plate helps to get the pig into motion when the pressure drop over the pig is relatively small (Wu and van Spronsen, 2005). Finally, a by-pass pig design which is shown in Fig. 2b is considered. This by-pass pig has an adjustable by-pass area by making use of a rotatable valve. The angular position of the valve determines the opening of the by-pass holes. The adjustable by-pass enables control of the pressure drop over the pig and thus control of the speed of the pig. This by-pass pig is therefore referred to as the speed controlled pig. Examples of speed controlled pigs can be found in Thuenemann and Wegjan-Kuipers (2003) and Money et al. (2012).

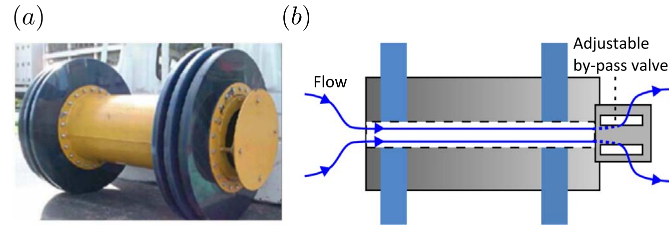

Fig. 2. (a) A by-pass pig with a deflector disk, taken from Wu and van Spronsen (2005). (b) Schematic of a by-pass pig with speed control. The by-pass valve can be adjusted to regulate the by-pass area.

The structure of the paper is as follows. In Section 2 a literature review is given on theory and correlations for by-pass pig geometries and the building block approach is explained. Section 3 describes the numerical setup which is used for the CFD calculations. Results obtained from the CFD simulations are discussed in Section 4. A summary of the results and possibilities for future research are given in Section 5.

2. Building block approach

In previous research the pressure loss coefficient of a bi-directional by-pass pig, K_{bidi}, was studied using CFD (Singh and Henkes, 2012). It was found that K_{bidi} can be successfully described by the Idelchik correlation for a thick orifice, as the bi-directional by-pass pig has a shape comparable with a thick orifice, see Fig. 1. For sufficiently thick orifices ($\frac{L_{pig}}{d} > 3$) the Idelchik correlation for a thick orifice reads (Idelchik, 1987):

$$K_{bidi} = 0.5\left(1 - \frac{A_0}{A_1}\right)^{0.75} + \frac{4fL_{pig}}{d} + \left(1 - \frac{A_0}{A_1}\right)^2, \tag{2}$$

where $A_0 = \frac{1}{4}\pi d^2$ is the cross-sectional area of the by-pass and $A_1 = \frac{1}{4}\pi D^2$ is the cross-sectional area of the pipe. The length of the pig is denoted by L_{pig} and f is the Fanning friction coefficient, which is determined by the Churchill relation (Churchill, 1977) using the Reynolds number defined in the horizontal by-pass area, that is $f = f(U_{bp}d/\nu)$. Here it is assumed that the walls of the by-pass area are hydrodynamically smooth, which implies that the friction factor is not a function of the wall roughness. This correlation for a thick orifice can be regarded as a linear combination of the loss associated with the inlet of the pig (contraction loss), the by-pass area of the pig (wall friction), and the outlet of the pig (expansion loss), see Fig. 3.

The use of this 'building block' approach to model the pressure loss coefficient of a by-pass pig has been suggested in previous work (Nguyen et al., 2001a, 2001b), and was validated recently with CFD for a bi-directional by-pass pig (Singh and Henkes, 2012; Azpiroz et al., 2015). In this paper it is attempted to use this building block approach for a more general class of by-pass pigs, namely the disk pig and the speed controlled pig, as depicted in Fig. 2. In order to model these more complex shaped pigs it is suggested to modify the last term of Eq. (4). This last term is associated with the pressure loss of a sudden expansion, which is also known as the Borda-Carnot equation. This equation holds very well for a fully turbulent flow (Teyssandier and Wilson, 1974; Massey, 2012). It is important to note that the Borda-Carnot equation, along with the other contributions in Eq. (2) are