International Journal of Multiphase Flow 94 (2017) 17–30

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

An inertial two-phase model of wax transport in a pipeline during pigging operations☆

Andrea Boghi[a,*], Lloyd Brown[b], Robert Sawko[c], Christopher P. Thompson[c]

[a] School of Water, Energy and Environment, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK
[b] Science Deployed, LLC, Katy, Texas, United States
[c] AMAC Group, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK

ARTICLE INFO

Article history:
Received 26 September 2016
Revised 10 March 2017
Accepted 14 April 2017
Available online 15 April 2017

Keywords:
Pigging
Oil
Wax
Deposition
Pipeline
Modeling

ABSTRACT

Pig in pipelines performs operations for cleaning the pipe interior and internal inspection. In the past few years many 1D models have been developed to simulate the process because of their reduced computational cost; however, they rely on simplifications which are not always valid. In this paper, the results of a three-dimensional (3D) numerical investigation of the interaction between a waxy-oil and a dynamic sealing pig in a pipeline are presented. The results are obtained at a reduced computational cost by using a moving frame of reference, and an "injection" boundary condition for the wax deposited on the wall. The effect of the temperature and the wax particles' size has been investigated. The 3D results show the structure assumed by the debris field in front of the pig. In particular, a lubrication region at the bottom of the pipe, whose dimensions are temperature dependent, is shown. This information cannot be deduced from 1D modeling. The influence of the oil on the mixture viscosity and the internal bed dynamics are discussed. This work provides insights into the interaction between the debris field in front of the pig and pipeline hydraulics.

1. Introduction

Pipelines are the most common and safest way to transport oil and gas products. During operation, the pipeline walls suffer a deterioration process and can fail if they are not properly maintained. One part of pipelines maintenance procedure is "pigging" them regularly to prevent the increase of the wall roughness and the reduction of the internal diameter. The device known as "pig" is driven through the pipe by the flow of oil, scraping deposits from the pipe wall as it travels and is used to perform "pigging" operations. Pigging has been widely studied in the past few decades.

McDonald and Baker (1964) derived the first mathematical model on pigging. The model, valid for spherical pigs, was meant to be used for prediction of the liquid hold-up. Barua (1982) improved the model by removing some limiting assumptions and by considering the slug acceleration.

Kohda et al. (1988) proposed the first two-phase transient pigging model based on correlations. Minami and Shoham (1995) used a mixed Eulerian–Lagrangian approach to couple the transient two-phase flow with the pig motion. Hosseinalipour et al. (2007b) followed a similar approach, testing a transient model and comparing the results against experimental data.

Azevedo et al. (1996) developed an algebraic, 1D, hydrodynamic model to describe the bypass pig dynamics. The model coefficients were determined through two-dimensional (2D) Computational Fluid Dynamics (CFD) simulations of a Newtonian, incompressible fluid flowing in steady state conditions. The $k-\epsilon$ model was employed for the simulations.

Lima et al. (1998) and Lima et al. (1999) modeled the liquid removal operation in a gas pipeline. The 1D two-phase model has been solved via a semi-implicit finite difference scheme and the results have been successfully compared with experimental data. Nguyen et al. (2001b) solved the gas mass and momentum equations by using the method of characteristics (MOC) and the Runge–Kutta method. Nguyen et al. (2001c) and Nguyen et al. (2001d) applied the model to a bypass pig case, Nguyen et al. (2001a) to a curved pipe case, and Kim et al. (2003) experimentally verified the model.

Nieckele et al. (2001) developed a single phase fluid model, taking into account wall deformations, and coupled it with the pig momentum equation. A similar approach has been followed by Hosseinalipour et al. (2007a) to simulate the pig motion in gas pipelines.

☆ Modeling wax transport during pigging operations
* Corresponding author.
E-mail address: a.boghi@cranfield.ac.uk (A. Boghi).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2017.04.007

Xu and Gong (2005) developed a simplified pigging model to predict the pigging operation in gas-condensate horizontal pipelines with low liquid-loading. The model has been successfully compared with the OLGA code results. Tolmasquim and Nieckele (2008) developed a numerical code to simulate the transient oil flow in a pipeline during pigging operations and the results have been compared with field data.

In some works, the pig dynamics in dry conditions (no fluid flow) has been investigated. Hu and Appleton (2005) developed a dynamic model for a novel pig, designed to move both upstream and downstream, and verified the results against experimental data. Saeidbakhsh et al. (2009) analyzed the dynamics of small pigs in complex-shaped pipelines. The effect of the flow field was modeled by a time dependent force acting on the pig. The influence of the flow field was successively introduced. The fluid was considered incompressible by Lesani et al. (2012) and compressible by Mirshamsi and Rafeeyan (2015). In these three works, the dynamics of the system has been solved via a single ordinary differential equation.

Esmaeilzadeh et al. (2009) used the MOC to model the transient motion of a pig through liquid and gas pipelines. The simulation results showed good agreement with the gas-liquid pipeline field data. Deng et al. (2014) used the MOC to study the problem of column separation in gas-liquid pipelines during pigging operations. The simulation results were in good agreement with the field data.

Despite many models have been developed to describe the pig dynamics, most of them deal with gas flows and some of them with liquid removal in gas pipelines. In addition, all the cited models are limited to 1D domain. Waxy oils (wax-particles in oil mixture) in pipelines have been largely studied. Most of the literature focuses on two aspects: wax deposition in oil pipelines (Aiyejina et al., 2011), and wax removal from pipelines wall (Lima et al., 1995). Wang et al. (2005) studied the mechanics of wax removal in pipelines in dry conditions, while Wang et al. (2008) repeated the experiments with the oil flowing in the test facility. The tribological behavior of waxy oil subject to pipeline pigging has been investigated in the past few years using the fluorescence technique by Tan et al. (2015a); 2014) and with the portable microscopy technique by Tan et al. (2015b).

A few mathematical models tackle the wax removal from pipeline walls. An example is the one developed by Azevedo et al. (1999) and experimentally verified by Barros Jr et al. (2005). Other pigging models, based on experimental results, have been developed to predict wax deposition (Wang and Huang, 2014) and removal in pipelines (Huang et al., 2016). Wang et al. (2015) studied experimentally the influence of several parameters on the wax breaking process in order to determine the optimal de-waxing frequency and evaluating the pigging risks. A good review illustrating the forces acting on a bypass pig in operation was written by Galta (2014).

A few models studying the forces involved in the wax-removal process have been developed based on a mixed experimental-numerical procedure. In particular, Braga et al. (1999) considered the wax deposit as a linear elastic material and neglected the fluid flow, while Southgate (2004) included the oil flow, but considered the wax deposit as rigid and part of the pipe wall. The multiphase wax-oil flow in pipelines during pigging operations has been scarcely studied. An example is the 1D model developed by Hovden et al. (2003) with the OLGA 2000 code, where three different wax deposition models have been tested.

In this paper, a series of three-dimensional (3D) CFD simulations describing the interaction of the waxy oil with the moving pig are presented. Simulating the 3D flow is computationally demanding but has a two-fold advantage compared to the 1D approach: (i) it increases our understanding of the phenomenon, as it allows the visualization of the interaction between the pig surface and the wax chips; (ii) the results are less affected by modeling approximations.

2. Mathematical modeling

In this section, the mathematical model describing the dynamics of the oil-wax system in a pipeline, subject to pigging operations, will be illustrated.

2.1. Pig model

The main problem in representing the 3D pig motion numerically is due to the computational grid which must be warped in order to represent the pig displacement. Even though this can be realized with modern computational techniques, it is a computationally demanding operation.

A more convenient approach is to solve the problem in a frame of reference fixed to the pig center of mass, instead to an external observer, as done by Hosseinalipour et al. (2007b); Minami and Shoham (1995); Nieckele et al. (2001); Tolmasquim and Nieckele (2008) for 1D modeling. This is possible when the pipeline is straight, with a constant section, and the process is not investigated close to the pumping station or the outlet. Under these conditions, the computational domain does not change as the time goes by. As the pig advances, the wax is scraped to accumulate in front of the pig. Despite the debris field grows in time, it only occupies a small portion of the pipeline.

The relationship between the velocity in the absolute frame of reference, $\vec{v}_a$, and the one in the relative frame of reference, $\vec{v}$, is

$$\vec{v} = \vec{v}_a - \vec{v}_{pig} \tag{1}$$

where $\vec{v}_{pig}$ is the pig velocity. In order to determine this parameter, two hypothesis were introduced: the pig under investigation is of *sealing* type, i.e. no flow between the two sides of the pig, and the oil flow rate,

$$Q_{oil} = \int_{A_{pipe}} \vec{v}_{a,oil} \cdot \hat{n} dA \tag{2}$$

is constant. The mean oil velocity upstream the pig, U, is defined as

$$U = \frac{4Q_{oil}}{\pi D_{pipe}^2} \tag{3}$$

In order for the mass to be conserved at the interface between the upstream oil and the pig, it must be

$$v_{pig} = U \tag{4}$$

Eq. (4) can be written because the sealing pig has only one degree of freedom (1DOF), therefore: $v_{pig} = \vec{v}_{pig} \cdot \hat{n}$. In general, the pig could also spin around its axis. Nevertheless, the friction against the wall has been assumed high enough to prevent this. Since the oil flow rate is supposed to be constant, the pig velocity should be constant as well, by virtue of Eq. (4), therefore the pig inertial force, will not influence the dynamics of the oil-wax system. This is a reasonable approximation as the pig is most effective when it advances at a nearly constant, but not too high, speed as reported by Deng et al. (2014); Esmaeilzadeh et al. (2009); Nguyen et al. (2001a).

The pig operation is performed when the wax layer reaches a certain thickness h_w. Normally, for security purposes, h_w is very small compared to the pipe diameter. In order to represent this, the computational grid thickness should be of the same order of the deposit thickness, resulting in a large computational cost.

Supposing that the wax is uniformly distributed in the circular pipe, and it is pushed along the pig axis at the pig velocity, the