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A One-D approach for modeling transport and deposition of Black Powder particles in gas network

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ABSTRACT

Black Powder (BP) is a universal issue in sales gas transmission pipelines. It can cause serious problems in pipelines operations and instruments and contaminate customer supply. The objective of the present study is to develop a novel methodology for tracking the dispersion of Black Powder within gas transmission pipelines using a 1D approach based on the dusty gas assumption and the usage of analytical solutions of one-dimensional scalar advection/reaction equation. The study takes into account the deposition of Black Powder particles under different flow conditions, different particle diameters and different surface roughness. The proposed approach is applied to particle-laden flow in pipe segments with and without junctions and contrasted against CFD simulations based on the Discrete Phase Model (DPM). The results show that the finer particles with diameters dp < 1 (μm) can be transported easily to the downstream of the tree shaped network, while the larger particles dp > 1 (μm) are likely to settle rapidly near to the source location where Black Powder is generated and, consequently, forming beds. It is shown also that surface roughness increases the deposition rate of small particles dp ≤ 1 (μm) controlled by the Brownian forces. However, the deposition of larger particles in the inertial regime is not affected by the change in the surface roughness. These reported results are of significant practical interest, due to the lack of available data of Black Powder concentration in natural gas networks that have been reported in the literature to date.

1. Introduction

The transport of solid particles by turbulent flow occurs in a variety of natural and industrial processes. Among the later, the movement of solid particles such as Black Powder (BP) is becoming a prominent problem in major gas transmission networks over several countries around the globe (Baldwin, 1998; Tsochatzidis, 2008). The presence of BP in Gas pipelines has presented a range of challenges to the gas industry and can have a large number of detrimental effects in pipeline operations such as reducing flow efficiencies, fouling of compressors, blocking of orifice meters, contamination of instrumentation and control valves.

Evidence collected so far, points to the fact that BP particles are generated when hydrogen sulfide (H_2S), carbon dioxide (CO_2) or oxygen (O_2) are present in the gas or by bacterial corrosion of the internal walls of the pipelines (Sherik, 2007, 2008; Sherik et al., 2008; Cattanach et al., 2010). BP is known to contain primarily 81% iron oxides (Godoy et al., 2005; Tsochatzidis and Maroulis, 2007) and, in other cases, a mixture of iron oxides and iron sulfides (Baldwin, 1998; Godoy et al., 2005; Sherik, 2007; Tsochatzidis and Maroulis, 2007; Sherik, 2008; Sherik et al., 2008; Cattanach et al., 2010).

The Black Powder deposits, which are mainly a set of very fine particles, can be readily transported through a transmission pipeline system by the pressurized gas flow. It is therefore important to be able to understand and predict the movement, deposition and re-entrainment of BP in a pipeline. The present paper is an effort in that direction which presents a novel methodology based on one-dimensional approach to analyze the Black Powder movement and shed some new light related to this topic.

Several theoretical and experimental research studies have been directed at understanding BP movement in pipelines (Smart, 2007a, 2007b; Tsochatzidis and Maroulis, 2007; Smart and Winters, 2008). All these works focused only on the notion of critical velocity required to keep solid particles in movement. BP movement in gas pipelines belongs to solid laden gas flows that are encountered in several engineering applications. Several studies

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considered solid–liquid flow transport in pipes such as the recent study reported by Morten and Gustavo (2015). Extensive theoretical, numerical and experimental studies were devoted to understanding diverse aspects of solid–gas flows such as aerosol dynamics, effect of the particle diameter, particle density, particle volume fraction, gas velocity on the gas–solid flow (Boothroyd, 1971; Friedlander, 1977; Hetsroni, 1982; Elghobashi, 1991; Hidayat and Rasmuson, 2005; Balachandar and Eaton, 2010; Xinxiang et al., 2011; Tenneti and Subramaniam, 2013), pneumatic conveying in both horizontal and vertical pipes (Tsuji et al., 1992; Mezhericher et al., 2011; Li et al., 2013, 2014), bends (Chu and Yu, 2008; Elsaadawy and Sherik, 2012) and simulations involving junctions (Li and Shen, 1996; Schneider et al., 2002) can be found. The results of these studies were limited to very simple systems and geometries which consisted of single or several pipes of limited dimensions and were not conducted to simulate a long-distance natural gas transmission network.

A full 3D computational fluid dynamics simulation (CFD) approach for large transmission networks with long pipelines is beyond present day CFD capabilities especially for multiphase flows. The use of one-dimensional (1D) approach, where the system geometry is formulated conceptually as a linear network of segments or volume sections (Ben-Avraham and Havlin, 1982; Sahimi et al., 1983; Bunde and Havlin, 1991; Rossman and Boulos, 1996; Makse et al., 2000; Fernandes and Karney, 2001; Kirkpatrick et al., 2003; Andrei-Mugur and Sanda-Carmen, 2012; Chahibi et al., 2013), presents a viable alternative. In this approach, variation of flow parameters, such as concentration, occurs longitudinally (along the pipeline length) as the gas/liquid is transported out of one segment and into the next. The concentration of solid particles within such a system is continually modified by the physical processes of advection, dispersion and source or sinks. These influence the concentration along the pipe whereby sources represent addition, through mechanisms like pickup of particles and sinks represent settling or deposition of particles on the pipe wall. The limitation of the 1D approach is naturally the limited information extracted compared with a full three-dimensional simulation and the application of such an approach rests on the assumption of a dusty gas behavior.

To model deposition and pick-up in the source term of the 1D approach, usage is made of semi-empirical knowledge developed so far on deposition and pick up rates. Previous relevant work on deposition rate of solid particle in turbulent flow can be found in Wood (1981); Papavergos and Hedley (1984); Fan and Ahmadi (1993); Lai (2002); Bouilly et al. (2005); Guha (2008) whereas that relevant to the prediction of the pickup rate from surfaces or stationary beds can be found in Sehmel (1980); Reeks et al. (1988); Nicholson (1988); Ziskind et al. (1995); Reeks and Hall (2001); Alloul-Marmor (2002). In addition phase split at pipe junctions remains an unknown in this approach and has to be modeled.

The present work attempts to model the behavior of BP movement in a pipe network using a 1D approach based on the dusty gas assumption and the usage of analytical solutions of steady one–dimensional scalar advection/reaction equation. In the dusty gas approach the gas-particles mixture is treated as a continuum (Davies, 1966; Crowe, 1982; Van Genuchten et al., 1982) and thus for solid–gas flow through a straight pipe, the particles follow the fluid (Balachandar and Eaton, 2010). For these reasons the flow can be treated as a pseudo-single phase flow with the fluid density depending on the local mass fraction of the particles. Such models require definitions of the volume concentration and the bulk density of the two phases. The definition of the bulk density leads to the notion of loading which is the ratio of the solid phase bulk density and the f1uid-phase density. The loading is an important parameter that characterizes the coupling between the phases. At low loading, the coupling between particles and background phase can he assumed to be one-way (Friedlander and Johnstone, 1957) and particles can be modeled as tracers (Balachandar and Eaton, 2010). For BP, present available evidence suggests that when flow is taking place, the volume fraction is less than 10^{-6} (Trifilieff and Thomas, 2009) and hence the condition of dilute gas–solid flow regime can be assumed.

The other important parameter is the Stokes number St (Friedlander and Johnstone, 1957). Stokes number is defined as the relation between the particle response time and the system response time:

$$St = \frac{\tau_p}{t_s}, \tag{1}$$

where $\tau_p = \frac{\rho_p d_p^2}{18\mu_g}$, ρ_p is the particle density, d_p is the particle diameter and μ_g is the gas dynamic viscosity. The system response time t_s is based on the characteristic length considered in the present study as the pipe diameter D and the characteristic velocity considered as the fluid average velocity inside the pipe U.

$$t_s = \frac{U}{D} \tag{2}$$

In the present cases of BP considered and believed to take place, the typical Stokes number is considered to be less and/or near the unity value which together with the low loading justifies the use of the dusty gas approach.

The objective of the present work is to develop a novel methodology for tracking the dispersion of Black Powder within gas transmission pipelines taking into account its deposition within smooth and rough surfaces, while pick up of particles may take place it is ignored in this work. The analytical solution of the advection-reaction equation and the approach is tested by considering particle-laden flow in pipe segments with and without junctions which were simulated using CFD based on the Discrete Phase Model (DPM). Three-dimensional CFD simulations were conducted as a support tool to the 1D approach developed. The 3D simulations were limited to small segments of the piping network and addressed the problem of phase split at junctions and particle depositions in straight pipes.

2. Governing equations

In the present study, the flow is assumed to be one-dimensional, along the x-direction, and to take place in a pipe of cross-sectional area A. The one-dimensional advection-diffusion-reaction equation can be written for the concentration C expressed in mass per unit volume as:

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = D_{diff}\frac{\partial^2 C}{\partial x^2} + S \tag{3}$$

where D_{diff} is the diffusion coefficient. For fully developed turbulent flow, the axial diffusion term $D_{diff}\frac{\partial^2 C}{\partial x^2}$ is negligible compared to the dominant advection term $U\frac{\partial C}{\partial x}$ and the radial diffusion which is responsible for deposition or pickup of solid particle is lumped in the source term S. The "source" or "sink" of the quantity C is formulated as $S = \pm\,\beta$ C.

In the case of settling of particles with a deposition rate β_{dep}, S is negative and means that a concentration quantity is subtracted from the upstream concentration. Significant quantities of Black Powder accumulate during long term (days, months and/or years). The analytical solution of the Eq. (3) was derived first by Van-Genuchten et al. (1982). However, for steady-state solution, Eq.