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Original Research Paper

Effects of fluid flow split on black powder distribution in pipe junctions

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ABSTRACT

In this study, CFD is used to investigate an important local phenomenon when populations of particles are split within junctions of gas piping networks. The particle-laden turbulent flow is studied using the k–ε turbulence model and the Discrete Phase Model DPM. The phase split is obtained for different working conditions including the effect of the particle diameter, the angle and the orientation of the branch. Particular attention is given to the effects of the flow rate of the gaseous phase when imposed at the outlets of the junction to replicate the flow control in real installations using valves.

The fluid flow split yields different flow rate fractions in the two sides of the junctions which generates complex flow topologies affecting the solids split remarkably. The straight prolongation of the main pipe is called the main while the other side of the junction is the branch with different angles and orientations. Under extreme cases of fluid flow split, vortices form at the entrance of the main and alter the trend of solids split remarkably. In addition, large particles undergo a slight settling affecting their spatial distribution upstream of the junction which adds a degree of complexity to the solids split.

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1. Introduction

The presence of Black Powder in gas pipelines is an important problem affecting several operating companies all around the world [1]. Solid particles such as food, cement, coal and pharmaceutical products in industrial applications, are products that are usually transported by gas streams within networks of pipes belonging to the pneumatic conveying technology [2]. In such networks, it is usually recommended to use symmetrical junctions to avoid mal-distribution of the conveyed particles [3,4]. In another scenario, pipe networks are designed for the distribution of clean gases and unsymmetrical junctions are common. However, under certain working conditions in gas transmission networks, corrosion might cause the generation of solid particles. These with a general composition of iron oxides and sulfides, is what is commonly known as Black Powder, and form and propagate randomly inside the gas piping network [5,6]. The ideal, but very difficult to achieve in practice, safety procedure consists in eliminating the sources of Black Powder completely. In fact, experience shows that attempts to eliminate the formation of Black Powder are still not satisfactory due to the complexity of the task and the ever present industrial constraints [6]. Consequently, Black Powder must be controlled and monitored to minimize its effects on the equipment of gas producers and consumers. It is therefore necessary to understand the flow behavior of Black Powder particles under different working conditions to develop reliable filtering strategies.

It is evident that the trajectories of the particles are strongly affected by the behavior of the gaseous phase. Several references, in the literature of single phase flows, discussed the occurrence of complex turbulent flow structures at piping junction. Most of the studies considered junctions with a side called run (or main, as it is named in this work) which represents the prolongation of the main pipe and another side called branch. The split ratio, usually, refers to the fraction of fluid phase in the branch. De Oliviera [7] conducted a numerical study of single and two-phase flows in T-junctions with a rectangular cross-section. He compared his findings, of single gaseous phase, with the experimental results of Popp and Sallet [8]. He found that, at about a fraction in the branch equal to 0.8 the inflow, the flow patterns in the run start exhibiting a complex three-dimensional behavior. When the split ratio, in the branch, was lower than 0.8, De Oliviera [7] mentioned that only one recirculation zone was observed in the branch. Charron and Whalley [9] studied phase split in pipe junctions and explained that there exists a dividing streamsurface boundary, developing from upstream of the junction, which separates the streams accessing the main and the branch respectively. The position of the dividing streamsurface boundary, at a pipe cross-section upstream of the junction, was found to be a function of the split

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Nomenclature

C_D	drag coefficient
$C_{1\varepsilon}$, $C_{2\varepsilon}$	k–ε model constants
d	particle diameter (m)
D	pipe diameter (m)
g	gravitational acceleration (m/s^2)
G_k	production term in Eqs. (3) and (4) (kg/ms^3)
k	turbulent kinetic energy (m^2/s^2)
p	pressure (Pa)
Re	Reynolds number (ρuD/μ)
Re_{sph}	spherical-particle Reynolds number $(\rho d\lvert\vec{u}_p - u\rvert/\mu)$
St	Stokes number $(\rho_p d_p^2 u/18\mu D)$
t	time (s)
u	mean velocity (m/s)
u'	fluctuating velocity (m/s)
u_p	particle velocity (m/s)
x_i	coordinate in direction i (m)

Greek letters

α, β	angles of the junction (°)
ε	turbulent energy dissipation rate (m^2/s^3)
μ	fluid molecular dynamic viscosity (kg/ms)
μ_t	fluid turbulent dynamic viscosity (kg/ms)
ρ	Fluid density (kg/m^3)
ρ_p	Solid particles density (kg/m^3)
σ_k, σ_ε	Prandtl numbers associated with k and ε, respectively

ratio in the branch. Furthermore, complex turbulent flow field were seen at the entrance of the main at high split ratios due a vena-contracta phenomenon combined with a high adverse pressure in the same side of the junction. Neary and Sotiropoulos [10] also described similar turbulent structures for junctions in open channel flows. They mentioned the existence of the dividing streamsurface which is a curved shear-layer surface. They explained that the diverted flow, following curved trajectories, experiences an imbalance between the transverse pressure gradient, and shear and centrifugal forces which generates secondary vortices in the form of spiral turbulent structures. These secondary vortices can be generated in both sides of the junction. The complex turbulent structures should affect the behavior of particles in gas–solid flows as it will be shown in this study.

Studies on gas–solid flows in pipe junctions are scarce and have been mainly devoted to numerical simulation of nasal cavity and pulmonary airways, as in the work of Chen et al. [11], and experiments on pneumatic conveying, as in the work of Morikawa et al. [12], Morimoto et al. [13] and Guangbin et al. [14], with case-dependent semi-empirical models for pressure drop and phase split.

Few contributions, in terms of simulation of gas–solid flows at junctions can be found in the literature in the studies of Schneider et al. [3], Shirazi [4], Li and Shen [15] and Kharoua et al. [16], due to the complexity of the configuration and the important computational effort required in addition to the limited use of unsymmetrical junctions in industry due to mal-distribution constrains. Several multiphase models are available in the literature for such applications. Each multiphase model is devoted to certain gas–solid flow regimes only [17]. The advantages of the Lagrangian approach are the flexibility in terms of the particle diameter and size distribution [17]. In contrast to previous experimental and theoretical studies, Li and Shen [15] found, by numerical simulation, that for small particles of diameters equal to 1, 5, 10 μm and a solid phase density equal to 920 kg/m^3, the air split ratio affects the solid-phase split as well. Few studies were devoted to Y junctions with a bend placed upstream of it used usually in power plants to transport Coal or Lignite toward combustion chambers [3,18,19]. These studies focused on the mal-distribution in symmetrical configurations and proposed possible solutions to the problem.

It is clear that studies and detailed knowledge on solid phase split at pipe junctions are limited.

In a previous study, Kharoua et al. [20] imposed an atmospheric pressure boundary condition at the outlets of the junctions. The study illustrated the effects of an equal resistance, in the two sides of the junction, on the behavior of Black Powder particles in different flow conditions and geometrical configurations. The present study complements the previous work of Kharoua et al. [20] and extends it to different working conditions where the flow split of the continuous phase is imposed in the range 10–90% replicating the flow control by valves in real installations. The solid phase split is numerically simulated, in Y and T-type pipe junctions to assess the effects of the size of the particles and the configuration of the junction when the fluid flow split is imposed. Such information is important from a practical point of view since it helps tracking and quantifying Black Powder movement in gas transmission pipelines. The particles were injected using the Discrete Phase Model DPM and turbulence is modelled using the two-equation k–ε model. It is assumed that the Black Powder movement in pipelines is of the dilute type. This assumption is consistent with the usual concentrations of Black Powder in gas pipelines so far observed [21]. The numerical approach is validated using the experiments of Guangbin et al. [14] and Janssen et al. [22] before it is extended to other flow situations of cognizance to the Black Powder problem.

The next section presents the adopted numerical simulation methodology and the configurations of the junctions considered. Then, the results are discussed in the subsequent section followed by the main conclusions.

2. Numerical approach

The methodology of the present numerical simulation work is described in this section. The configurations considered were Y- and T-junctions. The gaseous phase is governed by the Reynolds Averaged Navier–Stokes equations while the solid phase is accounted for through a force balance equation applied for each particle. The boundary conditions and a brief description of the numerical tools and the simulation steps are presented in section 3.3 and 3.4 respectively. The simulations were conducted using the commercial software ANSYS FLUENT 14.0 [23].

2.1. Geometrical configuration and computational mesh

The particle-laden flow in Y junctions was validated with the work of Guangbin et al. [14]. The corresponding geometry is shown in Fig. 1a. Due to the complexity of the geometry a block of tetrahedral cells was generated nearby the junction (Fig. 1c). Within the straight pipes, the mesh was made up of structured hexahedral cells. Then, the work of Janssen et al. [22] was considered for the validation of the phase split in T-junctions with finer poly-dispersed sand particles. For all the cases considered, a grid independency test was performed with three different meshes. Values of the normalized wall distance y^+, for the cell adjacent to the wall,

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