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Physical mechanisms involved in slug transport and pipe blockage during horizontal pneumatic conveying

I. Lecreps [a,*], O. Orozovic [b], T. Erden [c], M.G. Jones [b], K. Sommer [c]

[a] TUNRA Bulk Solids Handling Research Associates, NIER, The University of Newcastle, Callaghan 2308, NSW, Australia
[b] Centre for Bulk Solids and Particulate Technologies, NIER, The University of Newcastle, Callaghan 2308, NSW, Australia
[c] Lehrstuhl für Verfahrenstechnik disperser Systeme, Technische Universität München, 85350 Freising, Germany

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ABSTRACT

Moving slugs of plastic pellets were investigated in-situ during low velocity pneumatic conveying in horizontal pipelines. Slug characteristics including the profile of pressure, pressure gradient, particle velocity, porosity, radial and wall shear stresses, aspect and behaviour were combined to obtain a complete picture of moving slugs. The objective was to gain unique knowledge on the physical mechanisms involved in slug formation, transport, and decay and the occurrence of pipe blockage. Slugs in both stable and unstable states were analysed. A strong correlation between particle velocity and wall stresses was found, which suggests that the stresses responsible for the high pressure loss characterising slug flow may result mostly from the transfer of particle impulses to the pipe wall. Most slugs were found to be denser at the rear where particle velocity was the highest, thus leading to slug shortening over time. This phenomenon was successfully modelled using both Newton's 2nd law and the ideal gas law and prediction of particle velocity showed good agreement with experimental values. In contrast, other slugs were found to extend due to the particles at the front moving faster than the particles at the rear. Pipe blockage was found to result from insufficient permeation of the slug by the conveying gas, indicating that sufficient material permeability is a condition for slug flow to occur.

1. Introduction

Despite increased interest in dense phase pneumatic conveying since the seventies and the development of special dense phase conveying systems, the real establishment of such systems for industrial applications has been somewhat slow. The resistance typically comes from practitioners for whom the random performances of low velocity pneumatic conveying systems result in too higher risk. In fact, even if operating a pneumatic conveying system constitutes a relatively easy task, the design of such a system is often problematic. Since the end of World War II, research teams in both industry and academia have been working actively to assist designers of pneumatic conveying systems by developing design guidelines for the selection of system parameters like pressure, mass flow rate and velocity of both the gas and solid phases. The goal is to furnish equipment manufacturers design tables, diagrams and equations to aid in the design of new conveying systems. While this has been satisfactorily achieved in the field of high velocity pneumatic conveying by integrating friction factors as in the transport of gas alone, the design of low velocity pneumatic conveying systems and particularly slug flow conveying systems still remains a problem. This is because the complex physical mechanisms involved in the transport of high particle concentrations in a gas phase have still not been fully understood. In fact, in dense phase, the flow phenomena occurring in the pipeline are influenced by not only the gas velocity, solid properties, pipeline direction and configuration and solid feeding devices, but also the particle–particle and particle–wall interactions that are of great importance and should be taken into account. In addition, the transport of solids by a gas stream can cause some unique phenomena that often are not encountered in gas–liquid flows or single-phase flows, like the production of electrostatic charges, which again increases the complexity of the flow phenomena and their description.

A frequent approach to describe and systematise slug flow pneumatic conveying consists of extrapolating the physical parameters characterising the conveying process, such as average gas velocity, slug velocity and pressure loss to the behaviour of individual slugs. However, since information such as number and length of slugs is usually unavailable and each individual slug is in a particular state of formation, stability or decay, generally little information can be gained. Therefore, the converse approach in which measurements performed on individual slugs are extrapolated to the entire pipeline has also been applied. This approach presents great advantages in that if sufficient information is available, the actual physical mechanisms leading to slug flow and the resulting pressure loss can be identified and put into equations, which in turn can be used to predict overall slug flow design parameters. Some workers including Ramachandran [1], Konrad

* Corresponding author. Tel.: +61 2 40339030.
E-mail address: isabelle.lecreps@newcastle.edu.au (I. Lecreps).

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[2], Mi [3], Krull [4], Mason [5], and Daoud [6] focused on observing slug flow and investigating experimentally some of the slug characteristics, usually the slug velocity and pressure gradient. While some general knowledge on slug flow could be gained, because usually only one or two characteristics were investigated, the mechanics of slug formation, stability and decay could not be identified. One of the issues is that because slug flow is a dynamic process, significant parameters such as slug porosity and internal stress states are particularly difficult to determine experimentally, in particular because the measurements must be non-intrusive to avoid flow disturbance. As a result, complex measuring devices must be specifically designed or adapted to this application. In addition, the variations of porosity and stresses along a slug or between slugs are generally low and their recording necessitates highly accurate measuring devices, which were not easily available until the last decade. The experimental studies of Niederreiter [7], Pahk [8], Lecreps [9] and Nied [10] in this area are particularly relevant.

Technological advances also gave rise to the development of numerical analysis, which are increasingly applied and permit slug flow analysis without the requirement of pneumatic conveying trials. Tsuji [11], Kuang [12], Wensrich [13] and Levy [14] are among the authors who took up the challenge of simulating slug flow pneumatic conveying using diverse approaches such as Discrete Element Methods, Computational Fluid Dynamics or a combination of the two. Numerical simulations have the advantage of identifying some precise physical phenomena that physical measuring devices would only pick up with difficulty. In addition, they can deliver a complete picture of a moving slug with data on local stresses, porosity, velocity, pressure and also shape. However, computer simulations rely on many assumptions and require pre-calibration of the models, which usually necessitate experimental data. In addition, most simulation works consider steady-state slug flow and a short length of pipe. Thus, those results are often more qualitative than quantitative. Only in recent years, simulation results for unstable slug flow became available [15].

This paper deals with detailed in-situ investigations of moving slugs during pneumatic conveying in horizontal pipelines. It addresses both experimental and theoretical investigations performed with the aim of identifying the main physical mechanisms playing a role in the formation, transport and decay of slugs and the occurrence of pipe blockage. In particular, focus has been on the mechanisms driving the flow instabilities and leading to pipe blockage through establishment of relationships between profiles of pressure, porosity, particle velocity and wall stresses along moving slugs. By combining all those characteristics, a unique insight into the physical mechanisms involved in the transport of slugs in horizontal pipes was obtained. Slugs in both steady and unsteady states as well as occurrence of pipe blockage were analysed.

2. Thirty five years of research to understand slug flow

2.1. Flow observation

Ramachandran was possibly the first to study the flow of solid–gas mixtures using long transparent pipes to enable flow observation in large pipe diameters [1]. He noticed that the ease of movement is better in the case of coarser particles due to lower compaction of the mass. He also noticed that the material follows different modes of flow along the pipeline and proposed that the increase of material velocity down the pipe may be due to the expansion of the air from higher to lower pressures, which leads to the increase of the size of the interstices between particles, i.e. decrease of the compaction degree which, in turn, leads to the increase of the particle velocity. However, no measurement was performed to verify this premise. When Konrad [2] proposed that the material is conveyed only in the slugs and in the regions just in front of and behind them with the material being picked up from the stationary layer by the moving slug, transported along the pipe and then dropped off the back of the slug to form a stationary layer of the same thickness, he actually suggested that slug flow is no steady-state transport. Also numerical results obtained by Levy [14] indicated that slugs are continuously created and destructed. Further, Kuang traced numerically the process of particle exchange between the settled layer and horizontal moving slugs [12]. He found that the particles in the centre of a settled layer move into the upper part of a slug while the particles initially located in the lower part of a settled layer move into the lower area of the slug. Nevertheless, many workers including Konrad [16] assumed that plugs are like moving packed beds with all particles within each plug fixed relative to each other and moving with the same velocity, even though the transport occurs in a wave motion.

2.2. Particle, slug and gas velocity

Tomita investigated slug flow pneumatic conveying in a horizontal pipeline numerically and found that the gas velocity increases preceding the slug arrival. He mentioned that this would explain the jump of particles in front of the slug that has frequently been observed. He also found that the slug velocity is not always constant but changes sinuously [17]. Mi [18] and Krull [4] also measured the slug velocity and both established a linear correlation between slug and air velocity. Klinzing suggested as a rough estimate of slug velocity that it achieves about 70% of the air velocity in horizontal pipes [19]. Kuang [12] reported from numerical analysis that the gas mainly flows in the empty part of the pipe over a settled layer before encountering a slug, then redistributes itself to cover the entire cross-sectional area at the rear of a slug and finally becomes a partial flow again after passing through the slug. When the gas flow rate was low and the particles in a settled layer were stationary, he sometimes observed a backflow of gas inside the settled layer before and after a slug. Recently, Kuang also reported that an increase of the friction coefficient leads to the decrease of particle velocity but increase of solid concentration and pressure drop [15].

2.3. Slug length

Daoud noticed that the plug length decreases with the gas flow rate while for a given mass flow rate, the plug length increases along the pipe. He explained the changes of plug length and velocity along the pipe by establishing relationships based on mass balances at the front face and rear of the plug. In particular, he explained the increase in plug length along the pipe by the velocity difference between the front and rear of the plug [6]. It is however questionable whether those experimental results are indicative of a coming pipe blockage. Hitt also found that the waves increase in length along the pipeline [20]. Mason identified the same phenomenon and observed further over the pipeline short waves close together with a long gap before another series of waves [5]. This implied that the waves increase in length and then break up. Krull suggested that factors such as the pressure gradient and the slug velocity largely influence the length of a slug [4]. The numerical simulations carried out by Levy [14] also revealed that both the shape and the length of the slugs change along the pipe. Recent simulation results by Kuang [15] indicate that the slug length increases and the slug velocity decreases when the friction coefficient is increased.

All those results indicate that horizontal slug flow pneumatic conveying is far from being a steady-state process.

2.4. Porosity distribution/permeation through a slug

Aziz investigated the pressure loss variation across a plug according to the possibility for the gas to permeate through the plug [22]. He concluded that the pressure drop across the plug varies either linearly if permeation of the transport gas into the plug is allowed or in an exponential fashion if the plug is consolidated at its back and its initial dense state solid packing is maintained. He also concluded that the transport of material is made easier if a certain amount of permeation is possible. Kuang investigated the porosity distribution by means of computer simulation and found that the solid concentration is denser